PHD

An investigation of changeover sensitive heuristics in an industrial job shop environment

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Award date:
2007

Awarding institution:
University of Bath

AN INVESTIGATION OF CHANGEOVER SENSITIVE HEURISTICS IN AN INDUSTRIAL JOB SHOP ENVIRONMENT

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A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF BATH
FACULTY OF ENGINEERING OF DESIGN
DEPARTMENT OF MECHANICAL ENGINEERING
November 2006

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ACKNOWLEDEMENTS

I would like to thank my supervisors, Professor Antony R. Mileham and Doctor Linda Newnes for their guidance, support and encouragement throughout the course of this research.

The research has been carried out as part of the EPSRC's (Engineering and Physical Science Research Council's) Innovative Manufacturing Research Centre at the University of Bath (GR/R6759/010). I express my gratitude to colleagues at the University of Bath as well as at companies taking part in this research. Especially, I would like to thank Prabhu Ramkumar, Tim Hathaway and Mary Walker at TÜV Ltd for their valuable input to this work.

The Witness software support helpdesk and in particular David Wright has been very helpful, when I struggled with programming the various heuristics. I really appreciate the time he has taken to assist my research. Wen Chang Yang (Peter) was also a valuable support in assisting with Witness programming coding.

Furthermore, I am very grateful for the support from my family, who are always there for me and who have flown to visit me many times, carrying a lot of luggage for me and even coming over especially to help me paint my flat!

I am also thankful of the support from Dan Sirkett, who I thoroughly admire for always keeping both feet on the ground and putting up with my "freak outs".

I am indebted to all my friends in the department as well as across the campus, many of whom fall into both categories of being colleagues as well as friends. I have made many friends during my time at the University of Bath and cannot mention them all by names, but they know who they are, and I am grateful to all of them for being there through ups and downs.

ABSTRACT

The research in this thesis has investigated scheduling and Changeover Sensitive Heuristics (CSHs). The overall aim was to investigate the relationship between scheduling and changeovers and to develop and examine new scheduling heuristics that are intelligent enough to optimise both due dates and changeover requirements. Two new heuristics that incorporated the sequencing of jobs both according to product families and sub-product families were introduced. The new heuristics are named CSH12 and CSH12-K. A body of case studies have been undertaken. These are based on extensive data collected from the key collaborating company. In order to create generic data sets for a job shop environment, the case studies were extended to incorporate a range of parameters, such as several levels of processing times and job grouping strategies. Through discrete event simulation studies, the performance of the new heuristics has been compared to simple heuristics, semi-heuristics and existing changeover sensitive heuristics. In total, ten heuristics and two semi-heuristics were investigated. Scheduling according to product family (CSH1) compared to sub-product family (CSH2) was also studied and it is concluded that sub-product family sequencing performance better. Overall the new heuristics CSH12 and CSH12-K show a worthy performance and can reduce the changeover time the most through effective sequencing in a job shop environment with longer and shorter processing times. The research has also concluded that exhaustive heuristics perform better than non-exhaustive heuristics. Furthermore, CSHs are particularly effective for shorter processing times. This suggests that the choice of heuristic is more important for a mix of jobs with shorter processing times. Or the reverse, a mix of jobs with comparatively long processing times is less sensitive to the choice of heuristic. Additionally, the research revealed that product families with overall longer processing times result in higher percentage of tardy jobs. Thus, suggesting that dissimilar due date setting is beneficial for different product families. The research has determined the importance of considering appropriate scheduling and sequencing approaches, especially when changeovers have been addressed through design and organisational changes. The application of CSHs has demonstrated that an increase of jobs into the shop is possible. Hence, applying CSHs will achieve a strong competitive advantage.

LIST OF PUBLICATIONS

Journal

Eriksson K.M., Mileham A.R. and Newnes L.B. (in review). A comparison of changeover sensitive heuristics in a real job shop environment.

Eriksson K.M., Mileham A.R. and Newnes L.B. (accepted for publication). A comparison of short- medium- and long- horizon scheduling with sequence dependent changeover times.

Eriksson K.M. (2005) "Book Review - Planning and Scheduling in Manufacturing and Services – Author: Pinedo, Michael L.", *Proceedings of the Institution of Mechanical Engineers (I MECH E) Part B Journal of Engineering Manufacture*, Vol. 219, Issue B11, November, pp. 849-850 (2), ISSN 0954-4054.

Eriksson K.M. (2004) "Book Review - Scheduling Algorithms – Author: Brucker, Peter", *Proceedings of the Institution of Mechanical Engineers (I MECH E) Part B Journal of Engineering Manufacture*, Vol. 218, Issue B12, December, pp. 1845-1845(1), ISSN 0954-4054.

Conference

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Eriksson K.M., Mileham A.R. and Newnes L.B. (2003) A survey investigating current industrial scheduling practice among a cross-section of UK companies, *Proceedings of ICMR03, International Conference on Manufacturing Research*, 9 – 11 September 2003, Glasgow, United Kingdom, pp. 409-414, (full text in Advances of Manufacturing Technology XVII, Edited by Y. Qui and N. Juster).

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LIST OF EQUATIONS

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ATP	Average Time in Process
BOM	Bill Of Material
CO	ChangeOver
E	Earliness
ERP	Enterprise Resource Planning
ES	Expert Systems
FMS	Flexible Manufacturing Systems
GT	Group Technology
JIT	Just In Time
MPS	Master Production Schedule
MRP	Material Requirements Planning
MRP II	Manufacturing Resource Planning
$\mathbf{N_{A\text{-}D}}$	Number of tardy jobs for Product Family A - D
$\mathbf{N_T}$	Total number of tardy jobs
NP complete theory	Non-deterministic Polynomial complete theory
OM	Operations Management
OR	Operations Research
T	Tardiness
TSCT	Total Sum of Changeover Time (performance measure)
WIP	Work-In-Progress

LIST OF HEURISTICS

COVERT	Cost OVER Time
CR	Critical Ratio (Heuristic 3)
CR-CO	CR with ChangeOver Reduction (Heuristic 4)
CSH	Changeover Sensitive Heuristic
CSH1	Changeover Sensitive Heuristic (Heuristic 5)
CSH1-K3	Changeover Sensitive Heuristic (Heuristic 6)
CSH1-K3-CR	Changeover Sensitive Heuristic (Heuristic 7)
CSH2	Changeover Sensitive Heuristic (Heuristic 8)
CSH2-K3	Changeover Sensitive Heuristic (Heuristic 9)
CSH2-K3-CR	Changeover Sensitive Heuristic (Heuristic 10)
CSH12	Changeover Sensitive Heuristic (Heuristic 11)
CSH12-K3	Changeover Sensitive Heuristic (Heuristic 12)
EDD	Earliest Due Date
FCFS	First Come First Served (Heuristic 1)
FCFS-CO	FCFS with ChangeOver Reduction (Heuristic 2)
LCFS	Last Come First Served
LPT	Longest Process Time
LS	Least Slack
LSPO or S/OPN	Least Slack Per Operation
LWKR	Least Work Remaining
MDD	Modified operation Due Date
MWKR	Most Work Remaining
NINQ	Least number of jobs in queue
ODD	Operation Due Date
PT + WINQ	Processing Time plus Least total work in queue
PT + WINQ + LS	Processing Time plus Least total work in queue plus Least Slack
SPT	Shortest Processing Time
T-SPT	Truncated Shortest Processing Time
TWK	Total Work content due date setting
WINQ	Least total work in queue

Note: Changeover Sensitive Heuristics (CSHs) are outlined in detail in section 3.4 and Table 3.9.

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

Scheduling as a general concept is a very broad field and scheduling problems occur in many areas and exist in many different configurations. For example it could be scheduling the take off and landing of aeroplanes at airports or scheduling resources such as personnel in a company or at a hospital. Scheduling is a highly researched area as it frequently appears in many fields and on different levels. It is also an area, which although being greatly investigated, still offers challenges and has proved to be very complex.

The research reported in this thesis focuses on scheduling within the manufacturing sector. Manufacturing environments today are becoming increasingly more dynamic and competitive. In order to survive in this challenging environment, businesses have been forced to become more responsive and lean. Companies are competing on a global scale in a fast-moving world with customers requiring reliable delivery dates, high quality of products and services as well as quick responses to market changes. Suppliers are expected to deliver on time in increasingly small batches. To respond to these demands, businesses need to increase productivity and efficiency. This can be achieved through lead time and set-up time reduction, through the implementation of rapid changeovers and effective scheduling. Efficient scheduling provides a competitive advantage economically and when building close relationships with customers and suppliers. These relationships are changing as businesses become more global, a change facilitated through effortless high-volume data exchange over the internet. Businesses can develop a close relationship with customers and suppliers through the entire supply chain. Improved scheduling will have an effect on the accuracy of information that is exchanged, for example accurate lead times. Knowing their business and scheduling requirements will allow companies to assure more reliable delivery dates.

The strategic importance of successful scheduling in a business is reiterated by Morton and Pentico (1993) and Heizer and Render (2000), with the impact of such as scheduling on system performance and efficiency being highlighted by Pinedo (2002) and Rànky (1986). The importance and complexity of scheduling is addressed by many researchers and they highlight that schedules do not always provide sufficient results and appropriate scheduling and sequencing is difficult to achieve. Such objectives become more difficult to achieve as complexity increases resulting in businesses needing to be responsive and provide rapid changeovers.

1.2 OVERVIEW OF RESEARCH AIM, OBJECTIVES AND METHODOLOGIES

This research has explored the relationship between scheduling and changeover. Emphasis has been to study the impact of different scheduling scenarios on real industrial settings. The main research aim is;

To investigate the relationship between scheduling and changeovers and to develop and examine new scheduling heuristics that are intelligent enough to optimise both due dates and changeover requirements.

A range of objectives have been developed and investigated throughout the course of this research and they are outlined in detail in Chapter 4.

The research has investigated scheduling approaches currently used in industry as well as those that appear in the literature. The application of scheduling systems has been investigated and the operation of proposed scheduling and sequencing heuristics has been studied in detail. The impact of changeover time reduction involving major, minor and no reductions has been discussed. A range of heuristics, including simple dispatching rules as well as existing and new changeover sensitive rules were studied. The experimental factors involved processing time, changeover time reduction and machine utilisation. To assess the performance of the heuristics ten performance measures were compared.

The study has involved the application of different methodologies throughout the course of the research. An extensive literature review into the broad area of scheduling, together with a focused emphasis on scheduling and sequencing and their relationship to changeovers, took place. In order to investigate industrial scheduling approaches and to establish possible company collaborators a questionnaire survey was designed. Thereafter, pre-case study interviews took place, before embarking onto the main case study. A real industrial setting of an advanced electronic testing facility was modelled using the discrete event simulation software, Witness. The simulation models investigated a range of experimental scenarios, incorporating experimental conditions and factors outlined in the research objectives. The simulation experiments involved extensive validation and statistical analysis. Also the results of the simulation experiments were statistically analysed.

1.3 OUTLINE OF THESIS

Figure 1.1 outlines the structure of the research and the layout of this thesis. The literature review is composed of Chapter 2 and 3. Chapter 2 outlines common scheduling and sequencing denominations such as the classification scheme and gives a brief introduction to a range of scheduling solutions and approaches. Chapter 3 discusses in detail the relationship between scheduling and changeovers. The aim and objective of the research is outlined in Chapter 4. Chapter 5 and 6 describes the initial part of the research where a questionnaire survey and interviews took place to gather data for the industrial case study. The main study involving simulation model building and experimentation with Changeover Sensitive Heuristics (CSHs) is outlined in Chapter 7 and 8. Finally, Chapter 9 concludes the results of the research. The list of references is supplied in Chapter 10. All appendices, including simulation models and result files are supplied on CD-ROM. The CD-ROM also incorporates copies of the manuscript for the conference and journal papers listed.

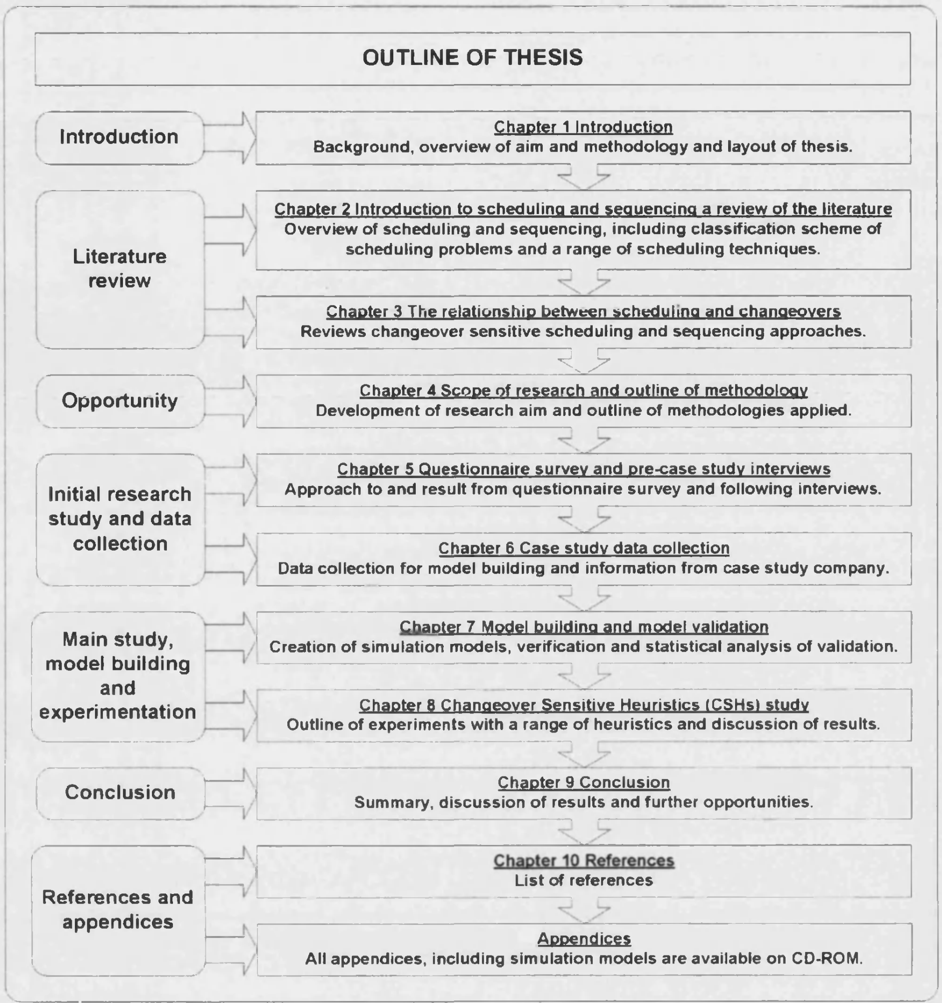


Figure 1.1: Structure of research and layout of thesis.

CHAPTER 2 INTRODUCTION TO SCHEDULING AND SEQUENCING – A REVIEW OF THE LITERATURE

2.1 INTRODUCTION

This chapter provides an overview of scheduling and production planning. An historic perspective is given as well as a review of research in the field and the impact of scheduling upon manufacturing. The areas covered in this chapter include the various approaches to scheduling including; mathematical techniques, heuristics, complexity theory and in particular the use of scheduling rules and their relationship/integration with machine changeovers. The standard classification scheme for scheduling problems is explained, including typical machine environments, job characteristics and performance measures. In particular the job shop configuration is discussed. These areas are set in relation to the current needs of industry and the importance of scheduling in this context is stressed.

In particular this chapter aims to review and examine the literature that has made a valuable contribution to these issues, in particular to:

- Investigate the types of scheduling approaches and heuristics applied.
- Analyse the extent of the use of scheduling systems and other approaches.
- Examine the effectiveness of the scheduling approaches used.
- Ascertain the interdependence between scheduling and sequencing and changeovers.

2.2 SCHEDULING WITHIN THE OPERATIONS MANAGEMENT COMMUNITY

This section has been included to clarify how and where scheduling occurs in a broader context. A discussion of scheduling and its connection to Operations Management (OM) is supplied and the different levels on which scheduling takes place are considered. An overview of areas related to scheduling is given.

Operations Research (OR) is an area belonging to operations management. The focus of OR is scheduling, where the activities are involved in the creation of goods and services (Heizer and Render, 2000) and the decision making process where system/operational performance within OR is examined (Winston, 1994). The OR community focuses on four key levels for their activity, such as medium and long term planning, as shown in Table 2.1.

Levels	Examples of Problems	Horizon
1. Long-range planning	Plant expansion, plant layout, plant design	2 – 5 years
2. Middle-range planning	Production smoothing, logistics	1 – 2 years
3. Short-range planning	Requirements plan, shop bidding, due date setting	3 – 6 months
4. Scheduling	Job shop routing, assembly line balancing, process batch sizing	2 – 6 weeks

Table 2.1: Classification of scheduling levels (Morton and Pentico, 1993).

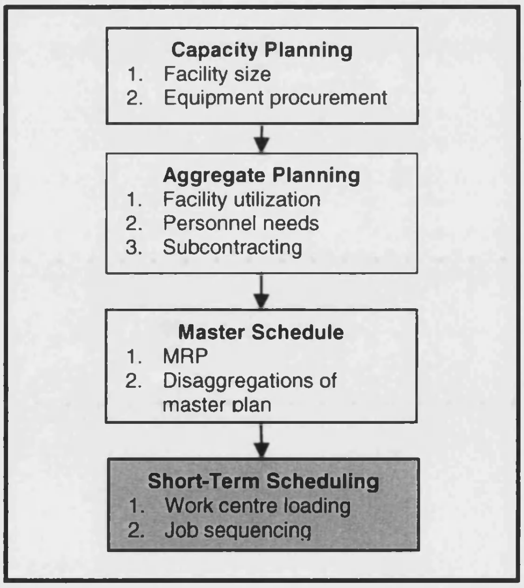


Figure 2.1: The relationship between capacity planning, aggregate planning, master schedule and short-term scheduling (Heizer and Render, 2000).

Figure 2.1 illustrates scheduling activates that occur such as capacity planning, aggregate planning, master schedule and short-term scheduling. These levels of scheduling also imply long term and short term planning, enabling the schedule to be examined across the whole business to individual machines (Rànky, 1986).

As shown in Figure 2.1 *capacity planning* deals with a high level of planning and will typically involve design of plant (factory) and manufacturing system. For capacity planning the question to be answered is whether the existing capacity is large enough to take on a job or not. The next planning step is *aggregate planning*. This stage regards medium-range scheduling and plans the use of facilities and inventories, deals with personnel issues and outside contractors.

The *Master Production Schedule* (MPS) phase involves *Materials Requirements Planning* (MRP) and the disaggregating of the master plan, where the aggregate plan is broken down and developed to an overall schedule for outputs. MRP systems are widely used in industry to assist the scheduling function in the interaction with other decision-making functions. It is a technique to determine material requirements that involves bill-of-material, inventory and a MPS. The MPS specifies what should be made and when to make it (Heizer and Render, 2000). The Bill Of Material (BOM), lists the components and volumes required to make each product. While discussing MRP it is appropriate to bring up its extension, Manufacturing Resource Planning or MRP II. MRP II contains an additional enhancement that converts output of production planning and control into financial terms (Silver *et al.*, 1998). The difference between MRP and MRP II is that MRP is an infinite capacity planning method and MRP II is a finite capacity planning method.

The short-term scheduling planning phase deals with the sequencing of jobs to each work station and the loading of these jobs onto the work stations (Rànky, 1986). The use of scheduling in this thesis focuses on the sequence of jobs at the shop floor level, i.e. short term scheduling. This is shown in Figure 2.2 (Pinedo, 2002) and is highlighted as the detailed scheduling area.

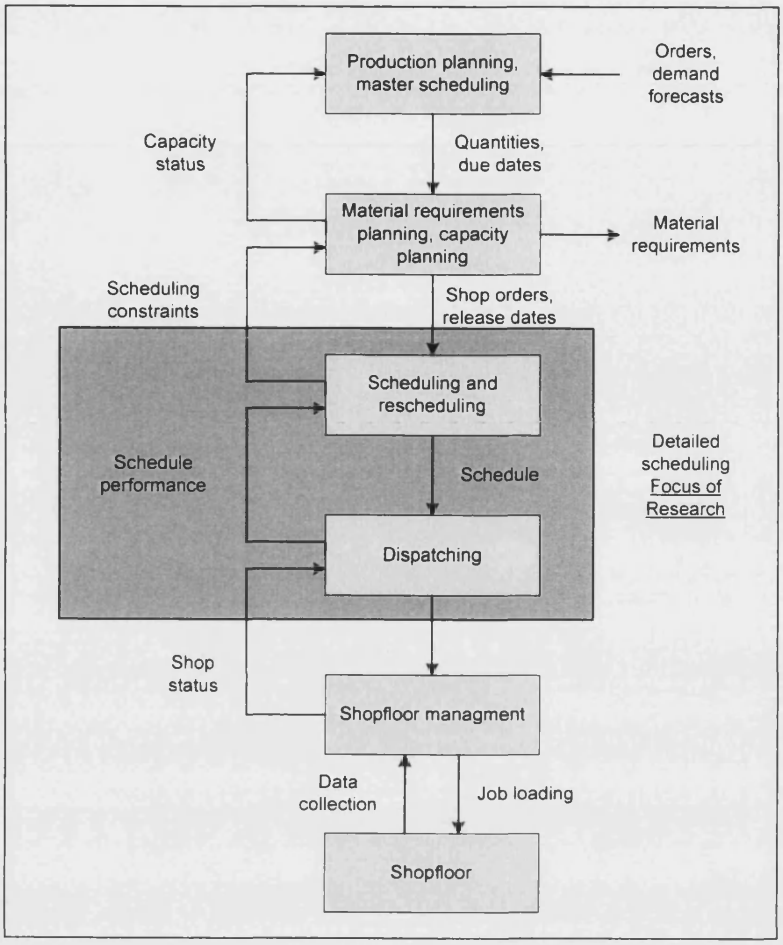


Figure 2.2: Information flow diagram in a manufacturing system (Pinedo, 2002).

2.2.1 Definitions of scheduling terms used in this thesis

This section defines and explains certain concepts regarding scheduling that are used in this thesis.

The concepts of scheduling and sequencing are commonly used together and the meanings of these two words can sometimes seem to be intertwined. However, it should be emphasised that scheduling and sequencing complement each other and can not be used interchangeable, Askin and Standridge (1993) provide a precise and clear definition.

*"**Sequencing** is the process of defining the order in which jobs are to be run on a machine. **Scheduling** is the process of adding start and finish time information to the job order dictated by the sequence".*

Heizer and Render (2000) and Cheng *et al.* (1999), use this approach. Rànky (1986) specifically define scheduling in manufacturing as *"scheduling in the manufacturing industry means the allocation of jobs to be processed on the specified machines in a given time span".*

Table 2.2 lists in chronological order, common definitions of scheduling and/or sequencing found in the literature. Several of the definitions in Table 2.2 include the explanation scheduling as the allocating of resources over time (Baker (1974), Graves (1981), Rànky (1986), Blazewicz *et al.* (1993), Lawler *et al.* (1993), Morton and Pentico (1993) and Pinedo (2002). Rembold *et al.* (1994) and Pinedo (2002) include optimisation of certain performance measures in their definition of scheduling. As Askin and Standridge (1993) point out, scheduling is closely linked to sequencing, which is the order to dispatch jobs to be processed in. The definition by Bellman *et al.* (1982) takes a more general stance, explaining that scheduling occurs anywhere where something needs to be planned, also in our daily life. Xiao-Feng *et al.* (2004) specifies shop floor scheduling naming resources such as machines and materials. Table 2.2 is included to summarise and compare common definitions of sequencing and scheduling.

The research described in this thesis concerns scheduling and sequencing of jobs at a shop floor level. The research has investigated alternative scheduling approaches and scenarios for the dispatching of jobs.

Author	Definition
(Baker, 1974)	"Scheduling is the allocation of resources over time to perform a collection of tasks."
(Graves, 1981)	"Production scheduling can be defined as the allocation of available production resources over time to best satisfy some set of criteria."
(Bellman *et al.*, 1982)	"The scheduling problem is the problem which arises inevitably whenever we want to make a daily routine for any planned work."
(Rànky, 1986)	"Scheduling is a process that relates specific events to specific times or to a specific span of time. Scheduling in general involves the order and timing of assigning resources to specific orders."
(Askin and Standridge, 1993)	"Sequencing is the process of defining the order in which jobs are to be run on a machine. Scheduling is the process of adding start and finish time information to the job order dictated by the sequence".
(Blazewicz *et al.*, 1993)	"In general, scheduling problems can be understood very broadly as the problems of the allocation of resources over time to perform a set of task."
(Lawler *et al.*, 1993)	"Sequencing and scheduling is concerned with the optimal allocation of scarce resources to activities over time."
(Morton and Pentico, 1993)	"Stated most generally, scheduling is the process of organizing, choosing, and timing resources usage to carry out all the activities necessary to produce the desired outputs and the desired times, while satisfying a large number of time and relationship constraints among the activities and the resources."
(Rembold *et al.*, 1993)	"It (scheduling) involves the time ordered arrangement of a set of jobs (parts) to be processed on a set of processors (such as machines) to optimize some measure of performance."
(Pinedo, 2002)	"Scheduling deals with the allocation of scarce resources to tasks over time. It is a decision-making process with the goal of optimizing one or more objectives."
(Xiao-Feng *et al.*, 2004)	"Scheduling involves the determination of the sequence of operations to satisfy several conditions and goals concurrently. It is the process where limited resources, such as machines, material and tooling, are allocated over the time horizon among both parallel and sequential activities."

Table 2.2: Common definitions of the concept scheduling.

For this thesis the following definitions will be used:

Resource: facilities, machines, employees and services Rànky (1986).

Job: product, part or process of producing a number of parts.

Machine: machine, processor, work centre, work station and facility.

2.3 COMPLEXITY THEORY AND REALISTIC SIZED SCHEDULING PROBLEMS

Complexity theory (Garey and Johnson, 1979) can also have an impact on scheduling. This is evident when computational problems are classified according to how easy or how hard they are to solve. Many scheduling problems are hard to solve and are complex in their nature. This is one of the major reasons why the area of scheduling is researched to such an extent. It is difficult, and in many cases impractical not to say extremely difficult to find an optimal solution for numerous scheduling problems. *"Complexity theory provides a mathematical framework in which computational problems can be studied so that they can be classified as 'easy' or 'hard'"* (Lawler *et al.*, 1993). Authors approach complexity using different models e.g. such as the Deterministic Turning Machine (DTM), (Blazewicz *et al.*, 1993). Whereas Lawler *et al.* (1993) and Brucker (2004) prefer to use the description of a standard programming language.

2.3.1 Scheduling problems and NP-complete theory

The reason that it is difficult to find an optimal solution in scheduling is the so-called NP (non-deterministic polynomial) –complete theory. A problem belonging to the NP class requires a number of computational steps which grow exponentially with the input (Lei *et al.*, 2002). The class of problems that can be solved in polynomial time are denoted P. NP class problems are classified into the categories of *NP-complete*, *NP-hard* and *strongly NP-complete* problems. To decide if the computational problem, or more specifically in this case, a scheduling problem, is 'easy' or 'hard' to solve, the number of computational steps required, to reach the solution is measured.

Most scheduling problems are *optimisation problems* and each optimisation problem is also associated with a so called *decision problem.* An optimisation problem aims to find a solution for which a certain objective function is at its optimum, and has reached an *optimal solution.* A decision problem, on the other hand, is a problem where the solution can take only two values, either "yes" or "no". A decision problem is no more computationally difficult than the corresponding optimisation problem. This means that if an optimisation problem has a solution then the decision problem has a solution. On the other hand, if the decision problem is computationally 'hard', then the corresponding optimisation problem is also 'hard' (Blazewicz *et al.*, 1993). To find out if a computational problem is 'easy' or 'hard' it is therefore convenient to attempt to solve the decision problem and hence find out the difficulty of the problem (Lawler *et al.*, 1993).

Scheduling problems may involve a number of variables, such as, different shop floor configurations, a large number of products, limiting resources such as machines and employees and multiple constraints. Such problems are often known as NP-hard problems (Xiao-Feng *et al.*, 2004). For example in a manufacturing environment an increase in jobs and/or machines creates an increase in possible schedules, implying an increased complexity of the scheduling problem. Figure 2.3 gives a guideline of the number of possible schedules that can exist for real industrial problems. For instance; if the number of machines is ten and number of jobs is ten, the graph in Figure 2.3 illustrates that $1*10^{64}$ solutions are possible. This means that finding an optimal schedule among such a high number of possible solutions can indeed be very hard.

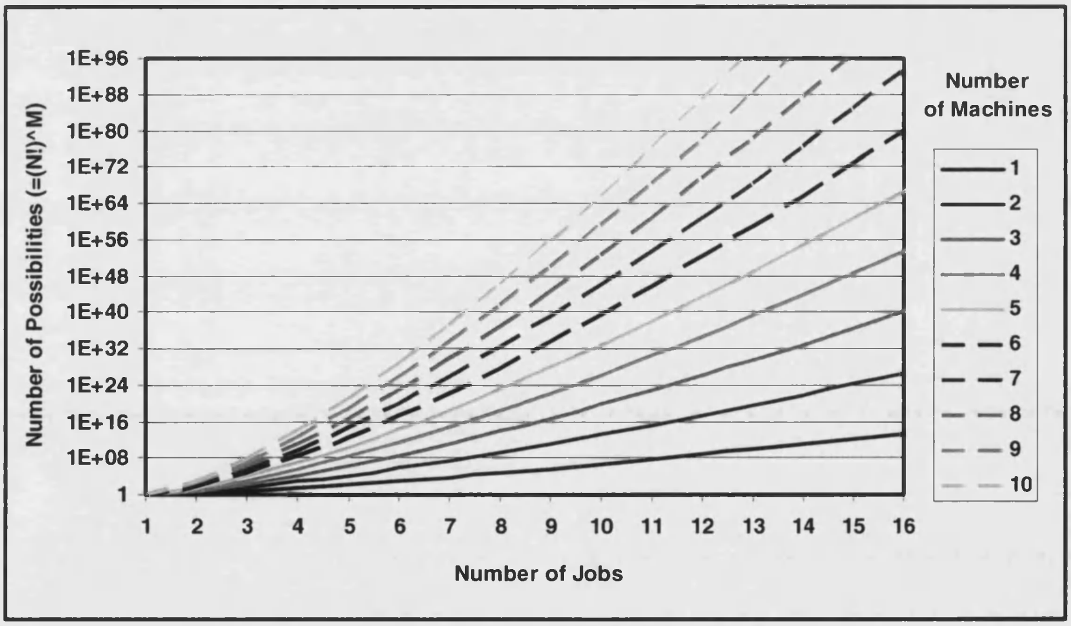


Figure 2.3: Number of possible schedules.

Examples of common NP-complete scheduling problems and when a problem is NP-complete, NP-hard or strongly NP-complete will be discussed in the next chapters. It may seem discouraging that many scheduling problems are optimisation problems and therefore also classified as NP-hard problems.

However, not all NP-hard problems are equally hard and in the following sections that deal with algorithms and heuristics it will be shown that even if an optimal and most favourable solution does not exists there might be "good enough" and practically useful solutions.

2.4 CLASSIFICATION OF SCHEDULING PROBLEMS

This section explains the nomenclature and framework applied to scheduling problems, which are commonly used throughout the literature. Its application enables the identification of the type of scheduling problem being investigated using information such as the machine environment, processing characteristics and optimality criteria studied. Lawler *et al.* (1993), Blazewicz *et al.* (1993), Pinedo (2002) and Brucker (2004) all provide similar descriptions of the framework and notation for scheduling problems. Pinedo (2002) especially provides a detailed review.

The framework and notation for scheduling problems is divided into four components, namely job data, machine environments, job characteristics and performance measures. The latter three are commonly represented in a three-field classification on the form $\alpha \mid \beta \mid \gamma$. Each of the nomenclature characteristics are displayed in Tables 2.3, 2.4, 2.6 and 2.7. It should be noted that although different authors report on different characteristics and number of optimality criteria, the main ideas are the same. Each of the components and related literature are critiqued in the following sections. The first section defines the characteristic and the terminology for job data, machine environments, job characteristic and performance measures. Thereafter a section discussing and critiquing other terms related to scheduling follows.

2.4.1 Job data

Throughout the literature the notation for basic scheduling problems has found to be that the *number of jobs* is denoted by n and the *number of machines* by m. The subscript j refers to a *job* and the subscript i refers to a *machine*. The pair (i, j) denote the processing step or operation of job j on machine i.

Notation	Job data	Description
p_{ij}	*Processing time (processing requirement)*	Represents processing time of job *j* on machine *i*. This notation would be p_j if job *j* is processed on only one machine or if the processing time of job *j* does not depend on the machine.
r_j	*Release date (ready date)*	The time where job *j* becomes available for processing. It is the earliest time job *j* can start the first operation.
$f_j(t)$	*Cost function*	Cost function measures the time of completing job *j* at time *t*.
d_j	*Due date*	Due date represents the required completion date. The date that the job is promised to be shipped to the customer. Completion of a job after its due date could incur a penalty. If a due date *must* be met it is referred to as a deadline and denoted by $\bar{d}_j$.
w_j	*Weight*	Weight is a priority factor. It denotes the importance of a job in relation to other jobs in the system. Weight could represent inventory cost or the amount of value added to the job.

Table 2.3: Job data.

Processing times for a job on a machine may vary depending on which machine that processes the job or the processing time could change depending on the type of job. Time to process a job could be constant (no variation) for a certain machine or may be represented according to a distribution.

If job j is not allowed to begin processing until a certain time the release date will be indicated in the β field. If r_j does not appear in the beta field processing may start at anytime.

Due dates are present in this research. They are especially important as the number of late jobs and other due date related measures are considered. Due dates can be set according to Total Work Content (TWK) or decided depending on when the customer requires the finished product. Due dates can also be set for products made to stock (final inventory), but in this case due date setting becomes more complex and dynamic (Morton and Pentico, 1993). Section 2.5(f) details due date setting strategies.

2.4.2 Machine environments (α)

Machines can be arranged in a number of different shop configurations. For scheduling problems these machine environments have a specific notation and will appear in field α of the three-field classification. The characteristics for these machine or scheduling environments are fundamental for the scheduling approaches applied.

Notation	Machine environments	Description
1	*Single machine*	The simplest machine environment and is a special case of all other machine environments.
Pm	*Identical machines in parallel*	Job *j* requires a single operation and can be processed on any *m* identical machines in parallel. Noted M_j if job *j* is allowed to be processed on any machine that belongs to a given subset.
Qm	*Machines in parallel with different speeds (uniform parallel machines)*	Speed of machine *i* is denoted by v_i, (Pinedo, 2002), (or speed can be denoted s_i (Lawler *et al.*,1993) and (Brucker, 2004)). The time p_{ij} that job *j* spends on machine *i* is equal to p_j / v_i, assuming job *j* receives all its processing from machine *i*.
Rm	*Unrelated machines in parallel*	A generalisation of uniform parallel machines, where speed is dependent on the job rather than on the machine. Means that machine *i* can process job *j* at speed v_i. The time p_{ij} that job *j* spends on machine *i* is equal to p_j / v_{ij}, assuming job *j* receives all its processing from machine *i*.
Gm	*General shop*	In a general shop each job is associated with a set of operations $O_{i1}, \ldots, O_{i,ni}$. Machines are dedicated and there are precedence relations between arbitrary operations. Job -, flow -, open -, and mixed shops are special cases of the general shop.
Fm	*Flow shop*	A flow shop has *m* machines in series. All jobs follow the same route, e.g. machine 1, machine 2 etc. and each job has to be processed on each one of the *m* machines.
FFc	*Flexible flow shops*	A generalisation of the flow shop and the parallel machine environments. There are *c* stages in series with a number of identical machines in parallel at each stage. Each job has to go through each stage, e.g. stage 1, stage 2 etc. At each stage the job requires processing on only one of the parallel machines and any machine can do the processing.
Jm	*Job shop*	There are m machines in a job shop and each job has its own predetermined route to follow. This can be described on the form O_{i1} *6* O_{i2} *6* O_{i3} *6* ... *6* $O_{i,ni}$ for $i = 1, \ldots, n$. Jobs can visit each machine only once or jobs may visit each machine more than once.
FJc	*Flexible job shop*	A generalisation of the job shop and the parallel machine environments. There are *c* work centres with a number of identical machines in parallel at each work centre. Each job has its own route through the shop and at each work centre the job needs processing on only one machine and any machine can do the processing.
Om	*Open shop*	There are *m* machines and each job has to be processed again on each of the *m* machines. Though, on some machines, the processing time may be zero. Job routing may differ from job to job and there are no restrictions regarding the routing.
Xm	*Mixed shop scheduling problems*	A combination of a job shop and an open shop.

Table 2.4: Machine environments (α).

The single machine environment has commonly been investigated in the scheduling literature. It is an environment where new algorithms and heuristics may be tested and compared. Even though the single machine is not common in a real industrial environment and may not always be representative, this type of problem can assist the understanding of a larger problem as it is possible that larger problems can be divided in smaller problems. Single machine environments may exist in for instance food manufacturing, when yogurt or liquid products are produced on one line. Although, this type of production would be classified as a flow shop (processing plant) if there are several work stations along the line. A single line flow shop may therefore be planned as a single unit (Meyr, 2000).

The parallel machine configuration is also commonly investigated in the literature, especially when set-up times are present. It can be divided into *identical*, *uniform* and *unrelated* parallel machines. Identical parallel machines (*Pm*) have the same processing times for job *j*. Uniform parallel machines (*Qm*) are machines in parallel with different speeds. For the unrelated parallel machine (*Rm*) environment the speed of the machines is job-dependent.

As mentioned above the flow shop (Fm) is an extension of the single machine. Examples of manufacturing where flow shops are applied are food manufacturing and health care products, such as tooth paste. If there are several parallel lines in a flow shop it is a so called flexible flow shop (FFc). Sequence-dependent set-up times can be significant in flow shops environments such as printed circuit board assembly, container manufacturing, and the printing industry (Ríos-Mercado and Bard, 1998). In a flow shop all items take the same route, whereas in a job shop products can take different routes. Figure 2.4 and 2.5 exemplifies this.

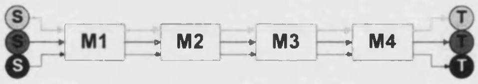


Figure 2.4: Example of routing in flow shop.

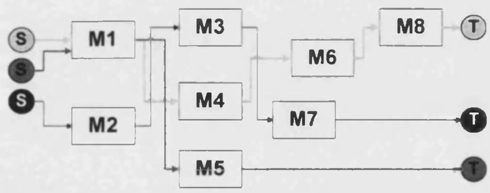


Figure 2.5: Example of routing in job shop.

The job shop (Jm) is a common manufacturing environment, but it is also a machine configuration that is especially difficult to schedule. For a job shop with many machines and a high number of product types finding an optimal schedule is not feasible (Figure 2.5). A classic example of a jobs shop is the machine tool milling shop, but the characteristics of a job shop exists in many areas for example customised one-time projects such as designing and building a house, large development projects and non-standard paperwork that flows across a desk (Morton and Pentico, 1993). The flexible job shop (FJc) is an extension of the job shop that incorporates parallel machines. One, several or all machines in the job shop can have parallel machines in this environment. The study reported on in this thesis has emphasised a job shop environment where parallel machines are available for certain processes.

In an open shop recirculation of jobs occurs and there is no specific routing of products. Those characteristics increase the complexity and scheduling difficulty further. The complexity and difficulty of solving of a scheduling problem rises with the number of machines and the number of products (Figure 2.3). Complexity also increases should set-up times, breakdowns and constraints be present. Such job characteristics are discussed in the next section.

Furthermore, the choice of shop configurations in manufacturing industry will depend on the number of products and type of manufacturing. Examples of this are outlined in Table 2.5. These types of shops can also be depicted in terms of product and process matrices. Figure 2.6 gives an overview of the types of shops found in various industrial sectors. The relationship between product mix, process pattern and production planning and scheduling is shown in Figure 2.7.

Type	Characteristics
1. Classic job shop	Discrete, complex flow, unique jobs, no multi-use parts.
2. Open job shop	Discrete, complex flow, some repetitive jobs and/or multi-use parts.
3. Batch shop	Discrete or continuous, less complex flow, many repetitive and multi-use parts, grouping and lot-sizing important.
4. Flow shop	Discrete or continuous, linear flow, jobs all highly similar, grouping and lot-sizing important.
5. Batch/flow shop	First half, continuous batch process; second half, typical flow shop.
6. Manufacturing cell	Discrete, automated, grouped version of open job shop or batch shop.
7. Assembly shop	Assembly version of open job shop or batch shop.
8. Assembly line	High-volume, low-variety, transfer line version of assembly shop.
9. Transfer line	Very high-volume and low-variety linear production facility with automated operations.
10. Flexible transfer line	Modern versions of cells and transfer lines intended to bring some of the advantages of high-volume production to job shop items.

Table 2.5: Scheduling environments (Morton and Pentico, 1993).

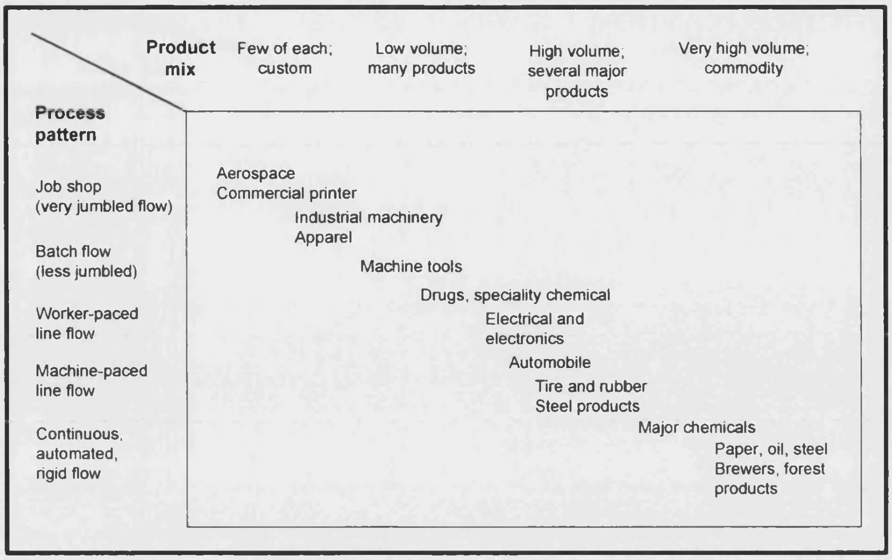


Figure 2.6: Product-process matrix (Silver *et al.*, 1998).

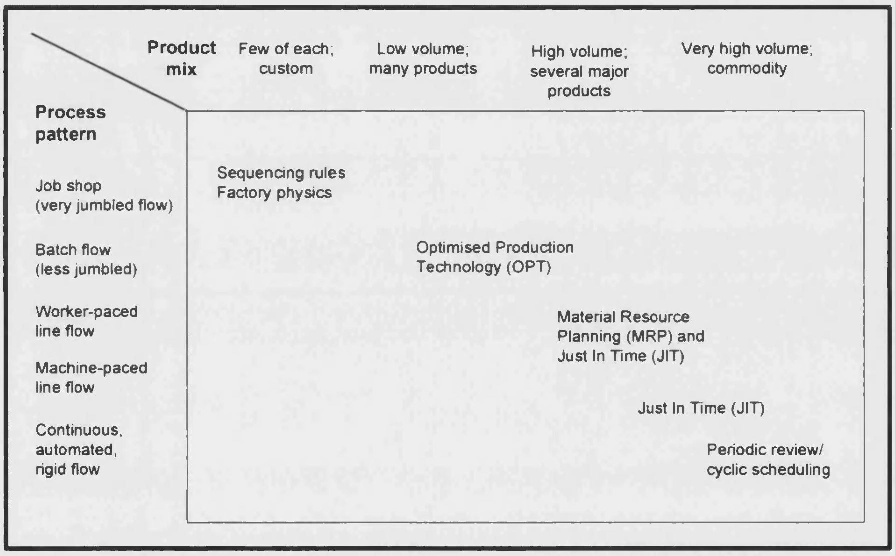


Figure 2.7: Production scheduling and the product-process matrix (Silver *et al.*,1998).

2.4.3 Job characteristics (β)

The β field is the second field in the three-field classification. Processing restrictions and constraints are specified in this field and one or several entries can be included in this field. Table 2.6 shows a range of job characteristics. Of specific interest in this study is sequence dependent set-up times (s_{jk}). A broader view of set-up time has been considered and the term sequence dependent changeover times will therefore be used throughout the thesis. This is described in detail in Chapter 3. Release dates (r_j) is another characteristics considered in this study, especially as one part of the study looks at scheduling over different time horizons and hence jobs are released at different times.

Notation	Job characteristics	Description
r_j	*Release dates*	If release dates are specified job *j* may not start processing before its release date.
s_{jk}	*Sequence dependent set-up times*	Sequence dependent set-up times between job *j* and job *k* are represented by s_{jk}. s_{0k} specifies the set-up time for job *k* if job *k* is first in the sequence and s_{j0} the cleanup time after job *j* if job *j* is last in the sequence. If the set-up time between job *j* and job *k* depends on the machine the subscript *i* is included s_{ijk}. If s_{jk} is **not** included in field β, set-up times are included in the processing time.
prmp	*Preemptions*	If preemption is allowed, a job started, can be removed before completion and replaced by another job.
prec	*Precedence constraints*	Precedence constraints may appear, in single or parallel machine environments, implying that one or more jobs have to be completed before another job is allowed to start. *Chains, intrees* and *outtrees* indicates different precedence constraints. A *chain* constraint for a job has at most one predecessor and at most one successor. For an *intree* the job has at most one successor and for and *outtree* the job has at most one predecessor.
brkdwn	*Breakdowns*	Indicates that unplanned (i.e. a certain distribution) breakdowns of machines take place and that machines are not continuously available.
M_j	*Machine eligibility restrictions*	If M_j is included, not all *m* machines are capable of processing job *j*. M_j denotes the set of machines that can process job *j*.
prmu	*Permutation*	The order or permutation of jobs through the first machine is kept throughout the whole process. Appear in flow shop environments that operate according FCFS.
block	*Blocking*	If the preceding machine has finished a job, but the successive machine is still processing a job and there is no buffer space, then the preceding machine cannot release its job until the successive machine has finished processing it, hence blocking occurs.
nwt	*No-wait*	No-wait means that jobs are not allowed to wait between two successive machines. Starting time on the first machine may need to be delayed to make sure the job does not have to wait in front of the second machine.
recrc	*Recirculation*	Can occur when in a job shop or flexible job shop when a job visits a machine or work centre more than once.

Table 2.6: Job characteristics (β).

2.4.4 Performance measures (γ)

Performance measures or optimality criteria are measures employed to evaluate schedules, i.e. they are used to assess the quality of a schedule. Finding an optimal scheduling solution to the objective function would be preferable. However, this might not always be possible and minimising one or several performance measures is the alternative option, i.e. minimising the objective function. Objective functions can be non due-date dependent or the objective may be a function of the due date. When classifying a scheduling problem the performance measure is denoted by γ. Table 2.7 provides a collection of performance measures used within scheduling. Table 2.7 divides measures into non due date and due date related criteria. The list is in alphabetic order, except for the criteria *sum of earliness and tardiness*, placed at the end, as it is a non-regular measure, meaning that earliness is non-increasing in C_j

(process time on the last machine for job j). A discussion of advantages and disadvantages of different performance measures follows.

The list in Table 2.7 is comprehensive and considers measures that appear frequently in the literature. Although, it can be argued that some of the measures are of more interest in real industrial applications than others. It is interesting to note that work-in-progress, average time in process and utilisation, criteria that often are of interest in the general area of manufacturing management, are not commonly applied in scheduling research. In scheduling the most common objective functions are *makespan*, *total flow time* and *weighted total flow time* (Brucker, 2004). Another common measure is *mean tardiness* (Baker, 1974). Further performance measures or combinations of the performance measures found in Table 2.7 may also be applied. From an industrial point of view, some of the performance measures may be less practical. Heizer and Render (2000) consider four scheduling criteria that they regard relevant to industry; *completion time*, *utilisation*, *work-in-progress* and *customer waiting time*. Utilisation is the time the machines are in use (percentage), i.e. the time jobs are being processed. The higher utilisation the more use of the machines and the more parts can be made. Utilisation is a common performance measure in production engineering, but it is not commonly found in scheduling research. Customer waiting time is an interesting performance measure in a real scheduling situation. It is also possible to apply this measure in order to prioritise certain customers. Another performance measure of interest in industry is average time in process (ATP_j) of jobs.

Notation	Performance measures	Description
	Non due date related performance measures	
ATP_j	*Average time in process*	The average time the jobs have spent going through the whole process.
C_j	*Completion time*	The time at which the processing of job *j* is finished.
C_{max}	*Makespan*	The total amount of time required to completely process all jobs, defined as max(C_1,..., C_n).
ΣC_j	*Total completion time (flow time)*	The sum of completion times of the *n* jobs being scheduled. Also referred to as *flow time.*
Σw_jC_j	*Total weighted completion time (flow time)*	The sum of the completion times is multiplied by a weight (w_j).
$\Sigma w_j(1 - e^{-rC_j})$	*Discounted total weighted completion time (flow time)*	Here costs are discounted at a rate of r, 0 < r < 1, per unit time. If a job is not completed by time t, an additional cost w_jre^{-rt} is incurred over the period [*t*, *t* + *dt*]. If the job is completed at time t, the total cost incurred over the period [0, *t*] is $w_j(1 - e^{-rt})$. The value of *r* is usually close to 0, around 0.1 or 10% (Pinedo, 2002).
$1/n\ \Sigma C_j$	*Mean completion time (flow time)*	The average completion time, where *n* is the number of jobs.
Util	*Machine utilisation*	Utilisation is the time the machines are in use (percentage), i.e. the time jobs are being processed.
WIP	*Work-In-Progress*	The average number of jobs being processed.
	Due date related performance measures	
CWT	*Customer Waiting Time*	The time the customer has to wait to receive a product, from order to delivery.
L_j	*Lateness*	Defined as $L_j = C_j - d_j$. Lateness has a positive value when a job is completed early and a negative value when a job is completed late.
L_{max}	*Maximum Lateness*	Defined as max(L_1,..., L_n) and measures the worst violation of the due dates.
N_T	*Number of tardy jobs*	The sum of tardy jobs. Defined as $N_T = \Sigma\delta(T_j)$ where $\delta(x) = 1$ if x > 0 otherwise $\delta(x) = 0$ or
Σw_jN_j	*Weighted number of tardy jobs*	Number of tardy jobs is multiplied by a weight (w_j).
T_j	*Tardiness*	Defined as $T_j = \max(C_j - d_j, 0) = \max(L_j, 0)$. The difference between tardiness and lateness is that tardiness is never negative.
ΣT_j	*Total tardiness*	Sum of tardiness of *n* jobs that gone through the system.
Σw_jT_j	*Total weighted tardiness*	The sum of the weighted tardiness of *n* jobs.
$1/n\ \Sigma T_j$	*Mean tardiness*	The average completion time, of *n* jobs.
T_{max}	*Maximum tardiness*	Defined as the job with the highest tardiness.
U_j	*Unit penalty*	The unit penalty of job j is $U_j = 1$ if $C_j > d_j$ otherwise $U_j = 0$. The unit penalty corresponds to the number of tardy jobs.
E_j	*Earliness*	Defined as $E_j = \max(d_j - C_j, 0)$. If a job is finished before the due date, it is early.
$\Sigma E_j + \Sigma T_j$	*Sum or Earliness plus sum of Tardiness*	A non-regular measure. The sum of all early jobs is added to the sum of all tardy jobs.

Table 2.7: Performance measures (γ).

It is common to multiply a performance measure with a weight (w_j), a priority factor indicating the importance of a job relative to other jobs in the system. The weight can vary depending on the process and product. The sum of the weighted completion time gives an indication of the total holding or inventory cost incurred by the schedule. Whereas, the sum of the weighted tardiness is a more general cost function (Pinedo, 2002). Multiply the number of tardy jobs by a weight is common. This is a measure of academic interest as well as often considered in practice, as it is easily recorded. Especially note that for the total earliness measurement, a high value may seem a good result, however, from a Just In Time (JIT) point of view, too early is considered a poor performance and early jobs may receive an earliness penalty. If the objective is on JIT, a performance measure that sums both the earliness and the tardiness values can be used. The number of late jobs (N_T), considers the overall number late jobs for all product types and may be split to measure different product families and job families. This could be used to investigate particular product type's lateness.

When investigating scheduling literature it was noted that many studies consider only one criterion or occasionally two. This is commonly the case when the study is theoretical in nature and the scheduling approach fails to apply an industrial case study. Investigating only one criterion limits the comparison between the scheduling approach tested and a previous study, unless the same performance measure is recorded. An approach tested over several performance measurements for a real problem offers a broader understanding of the scheduling problem and an enhanced indication of how the schedule would cope in such a situation. Additionally, for real industrial scheduling problems there will most probably be a number of criteria that are important. For example, a company testing new scheduling approaches might be interested in work in progress, the average time a job spends in the system and machine utilisation levels. Performance measures of interest may depend on the character of the business and may be company specific. Stoop and Wiers (1996) emphasize three areas where questions arise when measuring the quality of a schedule namely; which time horizon should be evaluated, what are the performance goals within different levels of the organisation and whether the schedule of a particular production unit could improve its performance at the cost of the performance of other production units.

The work described in this thesis considers both traditional scheduling performance measures as well as other measures that are of interest to industry. A range of performance measures were studied to provide a broad insight of the scheduling requirements.

2.5 SEQUENCING AND SCHEDULING CHARACTERISTICS

There are other terms related to scheduling problems in addition to the framework and nomenclature outlined in section 2.4. This section differentiates between these concepts when characterising scheduling problems. The problems can be represented by a number of characteristics such as static and dynamic to due date setting.

Table 2.8 shows common scheduling/sequencing approaches and typical applications.

Ref.	Classification	Application
(a)	Deterministic	The job list is fixed and there are a finite number of jobs to be processed on one or more machines.
(b)	Stochastic	The job list can increase over time. Job data may be known by distributions, but actual job data is first known after completion.
(c)	Forward	A schedule that starts as soon as requirements are known.
(d)	Backward	Considers due dates and schedules the final operation first and then the others in reverse order.
(e)	Lot-sizing	Useful to use when set-up/changeovers have a major impact on the schedule/sequence.
(f)	Due date setting	Due dates are often present when scheduling. The setting of due dates depends on customer demands and work content.
(g)	Enforced idleness	Machines may be kept idle on purpose for a certain time if waiting for urgent jobs due to arrive.

Table 2.8: Application of certain scheduling approaches.

(a) Deterministic scheduling

Scheduling problems are dealt with differently depending on their deterministic of stochastic nature. For the deterministic scheduling models it is assumed that there are a *finite* number of jobs that are to be scheduled. Lee *et al.* (1997) review deterministic scheduling.

(b) Stochastic scheduling

Stochastic scheduling also models a *finite* number of jobs. However, for stochastic scheduling problems job data such as processing times, release dates and due dates may be known in advance by distributions, but the *actual* processing times, release dates and due dates are known only after completion of the schedule and when jobs have been released and due dates set (Pinedo, 2002). A dynamic and probabilistic job shop is a form of stochastic scheduling, it is more realistic, but also the most difficult to schedule.

(c) Forward scheduling

Forward scheduling allocates resources in processing sequence with looking ahead from time thrown into process to time completed final process (Mori *et al.*, 1990). The schedule starts as soon as the job requirements are known. Forward scheduling designs a schedule even if it means it cannot meet all the due dates. It may also cause increased work-in-progress. Areas where forward scheduling may be used are machine tool manufacturers, hospitals and restaurants (Heizer and Render, 2001).

(d) Backward scheduling

Backward scheduling is performed backwards in time from due dates. It is usually applied for critical job scheduling or interval scheduling, where the work is expected to follow a redesigned schedule regardless of any changes (Morton and Pentico, 1993). As backward scheduling begins with the due dates and schedules the final operation first, it means that the schedule may not be feasible because of lack of resources. In practice, a combination of forward and backward scheduling is often used to achieve a trade-off between a possible schedule and due dates (Heizer and Render, 2001).

(e) Lot-sizing

Lot-sizing is an important consideration in scheduling decisions, especially when considering set-ups and changeovers, where lots may consist of orders from a number of customers and do so to avoid unnecessary changes (Meyr, 2000). For instance, for a production line that is producing paint, there might be a large range of different colours to produce, where long set-up times, including cleaning, are required when switching from one colour to another. From a cost and time point of view it is therefore not advisable to changeover between colours too frequently. However, producing an excessive stock of blue paint and then not leaving enough time to meet the due date for the yellow paint is no good either. The conclusion is that there needs to be a trade-off between how much blue paint to make before changing over to yellow. That is determining the lot size. Potts and Van Wassenhove (1992) have reviewed scheduling with *batching* and *lot-sizing*. They refer to batching as the decision of whether or not to schedule similar jobs continuously and lot-sizing as the decision on when and how to split a production lot of identical items into sub-lots.

Techniques for lot sizing include for example (Heizer Render, 2001);

- Lot for lot sizing where the lot size equals the demand.
- Economic Order Quantity (EOQ) which uses statistics to determine the most economic batch size to meet for example overall yearly demand.
- Part Period Balancing (PPB) which balances the storage cost and lot size/demand requirements.
- Wagner-Whitin algorithm which uses fixed time horizons to predict the requirement.

Other techniques such as repetitive lots utilise group technology methods and sequence dependent set-ups to establish the job sequence to minimise set-ups (Flynn, 1987b). To ensure that other job types are processed there is a maximum value set on the number of identical jobs to be processed sequentially. The use of scheduling techniques and sequencing to reduce set-up are of great importance in terms of industrial applicability. Other work includes that by Arosio and Sianesi (1993) who propose a heuristic algorithm that solves the problem of lot-sizing and sequencing in a single logic stage. Burman and Gershwin (1996) suggest a real-time dynamic lot-sizing heuristic subject to random set-up times. Their approach controls the system by controlling the bottleneck. Lot sequencing is performed using a greedy algorithm and lot sizing applies a closed loop feedback control policy. Clark and Clark (2000) used rolling horizon lot-sizing for a parallel machine problem with sequence-dependent set-up times. The problem is modelled using a mixed integer programming (MIP) formulation. An unusual and flexible feature of their work is that the formulation allows for multiple set-ups per planning period.

(f) Due date setting

In scheduling research, there are a number of methods used for setting due dates.

Techniques for due date setting include for example (Blackstone *et al.*, 1982) and (Veral, 2001);

- Constant allowance (CON) where the due date is set according to a uniform distribution in the future (salesman quote delivery).
- Number of operations in a job (NOPS).
- Total work content plus slack (SLK)
- Allowances proportion to work content (TWK).
- Regression analysis.
- Random (RAN) due date setting is performed arbitrarily (the buyer establishes the due date).

The total work content rule (TWK) is commonly applied in the literature (Jensen *et al.*, 1998) and (Jayamohan and Rajendran, 2000). Applying regression analysis to due date setting is a recently developed technique suggested by Veral (2001), where flow time characteristic of jobs and workstations are analysed and static rather than dynamic job data is used. When real case study data is used due-dates can be set according to practice in the real shop. For instance, Liao and Lin (1998) addresses scheduling in a home-use sewing machine company and assign the final due date according to how the company currently estimates due dates. This incorporate; estimated processing times, number of jobs that have not started their process and a 60 minutes allowance for set-up, work instructions, absence of workers and machine breakdowns. Furthermore, arrival time is considered and an allowance is given for the two departments that follow the one being scheduled. If a due date quoted by the customer is earlier than the estimate, the company will negotiate with the customer to assign a feasible due date. Due date setting in industry all depend on the nature of the company, the products or service they offer, customer demands and expectations, the work content, incorporation of set-up times and possible breakdowns etc.

(g) Enforced idleness

Morton and Pentico (1993) explain *enforced idleness*, i.e. that sometimes resources (machines) are kept idle in the case where there is a *"hot job"* (high priority job) due. It may be appropriate to apply enforced idleness if a job for one of the largest customer is due, or perhaps for a new important contract. There might be other cases were it is known that processing one job before another is an advantages, hence enforced idleness can be applied. Enforced idleness would not occur when a *nondelay* schedule is used (Silver *et al.*, 1998).

2.6 APPROACHES TO SCHEDULING PROBLEMS

This section focuses on scheduling approaches in terms of their industrial applicability. Firstly, the history of the scheduling area and its development, including major milestones in scheduling research, is described. Moreover, scheduling problems often referred to in the literature as "common" or "traditional" are included.

2.6.1 The development of Gantt charts

Scheduling became more prominent when Henry Ford's assembly line changed the way things were being made from craft to mass production. This is the time when Frederick W. Taylor formalised the principles of scientific management and developed Taylorism (Wikipedia The Free Encyclopedia, 2006b). A system designed to increase industrial output by rationalizing the production process. Henry L. Gantt was an industrial engineer and from 1887 to 1893 worked for the same company as Frederick W. Taylor, where he became his assistant. During World War I, Gantt constructed his now famous *Gantt charts*, a schedule representation of world-wide importance in the 1920s. Today Gantt charts are a common project management tool that show scheduled and actual progress of projects. Gantt charts are *"planning charts used to schedule resources and allocate time"* (Heizer and Render, 2000). It is a graphical representation of the duration of tasks against the progression of time (Kidasa Software, 2005). They provide a clear visual explanation of scheduling activities. Start and stop dates for activities are easy to spot and overlapping of activities or clashes will immediately be recognised. Perhaps these are some of the reasons to why Gantt charts are well liked.

Characteristics of Gantt charts are that they enable (Kidasa Software, 2005);

- Assessment of how long a project should take.
- Lay out the order in which tasks need to be carried out.
- Help manage the dependencies between tasks.
- Determine the resources needed.
- Monitor progress.
- Provide a tool to show how remedial action may bring the project back on course.

In general Gantt charts are useful for simple scheduling problems, but not complex scheduling problems dealing with a large number of parameters. Gantt charts used for loading show the loading and idle times of departments and machines, but the major disadvantage is that they do not account for production variability such as unexpected breakdowns or reworking of a job (Heizer and Render, 2000). A typical Gantt chart is shown in Figure 2.8.

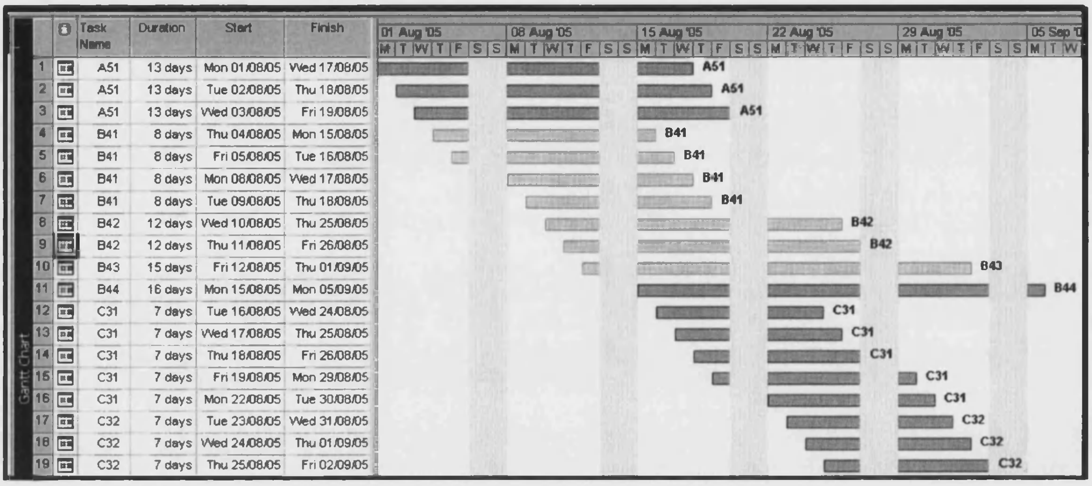


Figure 2.8: An example of a Gantt chart.

2.6.2 Algorithms and heuristics – definition of concepts

When finding solutions for scheduling problems, two main approaches are applied, these are *algorithms* and *heuristics*. These are defined in Table 2.9.

Approach	Definition
Algorithm	Finds an exact solution to an optimisation problem.
Heuristic	Finds possible solutions to an optimisation problem, but cannot guarantee an exact and best solution for a certain criteria.
Metaheuristic	A high-level strategy, which guides other heuristics when searching for solutions to optimisation problems.

Table 2.9: Definition of algorithm and heuristic.

An algorithm can find an exact solution to an optimisation problem (www.dictionary.com, 2005, Collins Dictionary, 2002). However, due to the fact that many scheduling problems are NP-complete (section 2.3), optimal solutions are not always available. Here heuristics can prove useful. A heuristic would not find an optimal solution to a problem, but a range of possible solutions (www.dictionary.com, 2005, Collins Dictionary, 2002 and Brucker, 2004).

These definitions for algorithm and heuristic are accepted in this thesis. However, in the literature the term *heuristic algorithm* have been used. Blazewicz *et al.* (1993) explain that where optimization algorithms can not be constructed *heuristic (suboptimal) algorithms* can be applied. These heuristic algorithms with analytically evaluated accuracy are termed *approximation algorithms*. Garey and Johnson (1979) explain that for algorithms the focus is no longer on finding an optimal solution, but a feasible solution and these are sometimes defined as heuristic algorithms. Consequently, heuristics are often called algorithms, although in their nature they are heuristics. The *genetic algorithm* (section 2.6.3(f)) is such an example. Therefore, an approach named algorithm does not necessarily give an optimal solution to a scheduling problem. In recent literature the concept of metaheuristic is introduced (Liu and Ong, 2004, Ruiz and Maroto, 2005 and Zoghby *et al.*, 2005). This is a top-level heuristic, which may include other heuristic. Examples are *genetic algorithm, tabu search* and *simulated annealing* (section 2.6.3(f)).

2.6.3 Review of scheduling techniques

This section gives a brief overview of approaches that have been applied to scheduling problems. Table 2.10 shows a summary and thereafter each approach is discussed.

Ref.	Technique	Explanation
(a)	Johnson's rule	An algorithm that solves the two-machine problem using makespan criteria.
(b)	Linear programming	A technique where the goal is to maximise or minimise a linear function subject to linear constraints, e.g. *the simplex algorithm.*
(c)	Integer programming / constructive algorithms	Includes approaches of constructive type that start with an empty schedule and gradually build up the schedule, e.g. *branch and bound* and *beam search.*
(d)	Dynamic programming	Solves a multi-variable problem by breaking up a large, unmanageable problem into a series of smaller, more tractable problems. Enumerates all possible solutions eliminating non optimal schedules.
(e)	Heuristic mathematical approaches	For large intractable problems that are NP-hard. Heuristics mathematical methods are designed to approximate large mathematical programs. Examples are *neighbourhood search, random sampling* and *lagrangian relaxation.*
(f)	Metaheuristic	Advanced heuristics start off with a schedule and then attempt to improve this. They are able to move from a local minimum to another area and do not stick on a local solution. Examples are *simulated annealing, threshold acceptance, tabu search, genetic algorithm.*
(g)	Disjunctive graph and programming	A disjunctive graph is a type of graph where the longest path (disjunctive arc or critical path) through the graph represents the makespan criterion. Hence, minimising the longest path will minimise makespan.
(h)	Agent-based approaches	Intelligent agents are part of artificial intelligence (AI) research. A software agent is a concept that describes software that acts for a user or other program in a relationship of agency. The idea is that agents are not strictly called up on for a task, but activate themselves. In scheduling, agents represent jobs and machines that negotiate with each other over the best "price" for processing.
(i)	Decomposition methods	A schedule is generated for a time period to a given point in time. Thereafter, a schedule is generated for the next time period etc. Examples are *machine-, job- and time- based decompositions.*
(j)	Bottleneck methods	Bottleneck methods schedule throughput to match the capacity of the bottleneck. *Bottleneck dynamics* are dispatch scheduling techniques, which forecast due date problems and critical resources dynamically.
(k)	Theory of constraints (TOC)	Theory of constraints (TOC) identifies operations that limit output, i.e. number of jobs processed. Constraints are for example machines, raw materials, supply procedures and training. The principles of TOC have been applied to scheduling.
(l)	Dispatching rules	A form of heuristics is *dispatching rules* or *priority rules.* Their use is common for scheduling problems where no optimal solution algorithm exists. Dispatching rules determine the sequence of jobs.

Table 2.10: Table of scheduling techniques.

(a) Johnson's rule

The work by Johnson (1954) is one of the seminal scheduling papers. Johnson studied a scheduling problem where a number of jobs were to be processed on two machines. Each machine could process one job at a time and each job needed processing firstly on machine one and thereafter on machine two. A decision rule was presented that gave an optimal schedule of the production minimising makespan. This rule is known as *Johnson's rule*. Johnson also discusses a three-machine problem and supplies a solution for a restrictive case. Garey *et al.* (1976) regarded the scheduling problem that can be solved with Johnson's rule the most complex for which an exact algorithm is known. This is still the case because of the computational intractableness of NP-completeness (section 2.3). This famous paper by Johnson (1954) set the direction of scheduling research that followed and resulted in much work being devoted to intractable problems of little practical consequence (Graves, 1981 and Dudek *et al.*, 1992).

(b) Linear Programming (LP)

Linear programming is a tool for solving optimisation problems and it is extensively used in the operations research area. The word "programming" means "planning" in this sense. The goal is to maximise or minimise a linear function subject to linear constraints. *The simplex algorithm* can solve large LP problems. Winston (1994) includes a thorough investigation of LP. In many maximisation and minimisation problems the objective function may not be a linear function or some of the constraints may not be linear. Such an optimisation problem is called a *NonLinear Programming problem* (NLP).

(c) Integer Programming (IP) / algorithms of constructive type

A more realistic approach in relation to LP is integer programming, although they are much harder to solve. Linear and integer programming methods are used for modelling of diverse types of problems in planning, routing, scheduling, assignment, and design. Integer programming algorithms include *"Branch and Bound algorithm"* and *"Beam Search"*. These are known as *constructive types*, meaning they start without a schedule and gradually construct a schedule by adding on a job at a time.

- The branch and bound algorithm

  The branch and bound algorithm has two procedures, branching and bounding. *Branching* divides problems into sub-problems, which are then again divided into sub-problems etc. *Bounding* calculates a *lower bound* on the optimal solution value for each sub-problem generated in the branching process (Blazewicz, 1993). The branching procedure is represented by a *search* or *branching tree* (Figure 2.9).

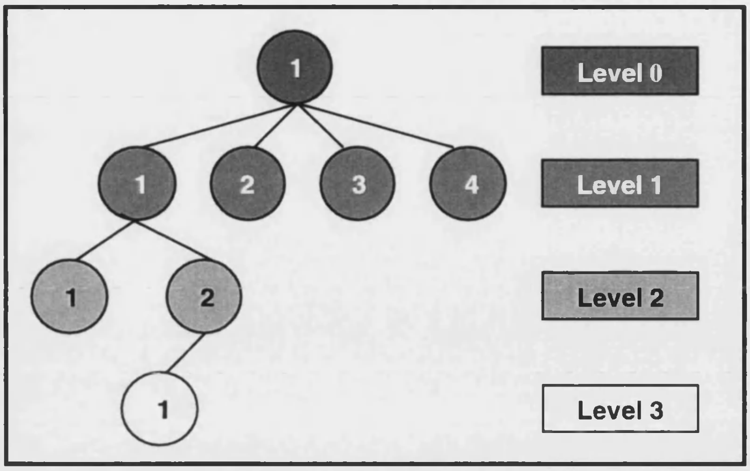


Figure 2.9: Example of search or branching tree.

Level 0 represents the original problem and the other levels consist of nodes representing sub-problems. In reality problems can have large amounts of branches where certain parts of the tree can simply be chopped off until only one possible solution is left (Morton and Pentico, 1993). Branch-and-bound is a technique for solving computationally difficult problems, but cannot solve all discrete and combinatorial optimization problems. A specific algorithm for a specific class of problems has to be designed. In general it is expected that problems with up to five machines and fifteen jobs can be solved (Dunstall and Wirth, 2005).

- Beam search/partial enumeration/filtered beam search

  The branch and bound can also be adopted to beam search where parts of the tree that are likely to be useless are cut off (Morton and Pentico, 1993), (Pinedo, 2002), hence providing a focused search.

(d) Dynamic programming

Dynamic programming is a technique where solutions are found by working backward from the end of a problem toward the beginning, thus breaking up a large, unmanageable problem into a series of smaller, more tractable problems. It enumerates in an intelligent way all possible solutions eliminating non optimal schedules. In dynamic programming there is no one algorithm that can solve all dynamic programming problems. For example the *simplex algorithm* (section 2.6.3(b)) can solve *all* linear programming problems. However, the dynamic programming approach solves a multi-variable problem by solving a series of single variable problems. In *deterministic dynamic programming*, given a state and a decision, both the immediate payoff and next state are known. If either of these is known only as a probability function, this is referred to as a *stochastic dynamic programming problem* (Trick, 1997) or *probabilistic dynamic programming* (Winston, 1994).

(e) Heuristic mathematical approaches

Both integer programming and dynamic programming solutions for small problems can be found exactly (Morton and Pentico, 1993). However, large problems have remained intractable as well as real problems since these problems are usually NP-complete. For this reason, heuristic methods were developed to approximate large mathematical programs. These are designated *"heuristic algorithms"* or sometimes *"approximation algorithms"*. This section introduces some early heuristics.

- Neighbourhood search

  A neighbourhood search is a particular example of a general nonlinear programming method called "hill-climbing" (Morton and Pentico, 1993). It can be described as a *"local search technique"*. The simplest form of a local search is a descent method that starts with an initial solution. A mechanism generates a neighbour to the current solution and if the neighbour has a smaller objective value, it becomes the new current solution otherwise the current solution is retained. This is repeated until a point where a local minimum is found (Liu and Ong, 2004). The disadvantage is that the iterative steps only move downhill on the objective function surface. This means that a local minimum might be found that is far from any global minimum. However, neighbourhood search techniques are often used in combination with other scheduling techniques, as a procedure to improve the solution method.

- Random sampling

  Random sampling is like neighbourhood search except that many random starting solutions are generated. This means that different neighbourhood searches can be performed and hopefully different areas of the search space are investigated and a good solution chosen. To differentiate between neighbourhood search and random sampling it can be said that neighbourhood search is an *"intensification strategy"* and a procedure for *"sticking with a winner"*, while random sampling is a *"diversification strategy"*, a procedure for *"it's time for a change"* (Morton and Pentico, 1993).

- Lagrangian relaxation

  In a scheduling problem there will be sets of constraints, such as machine capacity and certain precedences that should be enforced. If a constraint is disregarded or relaxed it may make the solution of the scheduling problem easier. This is where a so called *Lagrangian multiplier* can be applied (Pinedo, 2002), which solves a simple integer programming problem by dropping some of the constraints and paying a penalty proportional to the amounts by which they are violated. This is then combined with a search procedure. Morton and Pentico (1993), remark that Lagrangian relaxation can be a powerful tool, but it is complex to use and it is not yet a general purpose method.

(f) Metaheuristic

The disadvantage with a local search method, such as neighbourhood search, is that it is can stop at a local minimum and hence ignore a global minimum. Metaheuristics are more sophisticated and have been designed to overcome this disadvantage. The commonality between metaheuristics and local search is that they still need a local search heuristic initially, but they avoid getting stuck in a local minimum, by allowing a move from a local minimum to another area and therefore being able to explore the entire region. *Threshold accepting* and *tabu search* are two metaheuristics of *improvement type*, meaning they start out with a complete schedule and try to obtain a better schedule by manipulating the current schedule. An improvement type of algorithm is conceptually completely different from a constructive type. This section introduces a range of metaheuristics.

- Simulated Annealing (SA)

  Simulated Annealing (SA) was developed as a simulation model for describing the physical annealing process of condensed matter. In analogy with the annealing of metals, the temperature is made high in the early stages of the process for faster minimization or learning, it is then reduced for greater stability. For optimization problems simulated annealing was introduced by

Kirkpatrick *et al.* (1983). It both intensifies and diversifies. To avoid getting trapped at a local minimum SA sometimes accepts a neighbourhood move up hill that increases the objective value (Figure 2.10).

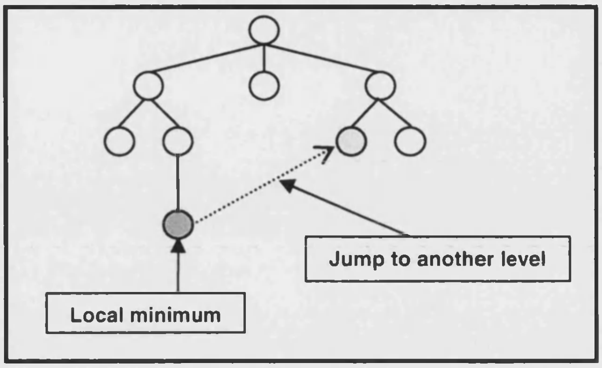


Figure 2.10: Example of a neighbourhood move up hill.

Simulated annealing (SA) has been applied to a flow shop scheduling problem with sequence-dependent set-up times (Parthasarathy and Rajendran, 1997a & 1997b). Compared to the tabu search procedure and simple heuristics, the SA approach is superior for weighted tardiness criteria. In order to improve performance of SA, Aydin and Fogarty (2004) have coupled SA with genetic algorithms (section 2.6.3(f)) to gain advantage from crossover and mutation. They have also taken advantage of distributed agents (section 2.6.3(h)) and created a "distributed evolutionary simulated annealing algorithm". This SA based approach performs better than the genetic algorithm on its own for a typical job shop problem.

- Threshold Acceptance (TA)

The Threshold Acceptance (TA) method, introduced by Dueck and Scheurer (1990) is a variant of the simulated annealing method and has been used within scheduling (Lin *et al.*, 1995, Meyr, 2002 and Lee *et al.*, 2004). TA uses a nonincreasing sequence of deterministic thresholds. In the procedure, the threshold values are gradually lowered, eventually reaching zero. During this process only improvements are accepted. The main difference between TA and SA is the different acceptance rules (Liu and Ong, 2004). The advantage here with TA is its simplicity. It is not necessary to compute probabilities or make random decisions. A disadvantage is that appropriate values for thresholds are unresolved. Furthermore, because SA and TA can leave a local minimum the disadvantage is that it is possible to get back to solutions already investigated (Brucker, 2004). To overcome this Brucker (2004) suggests the use of *tabu lists*, where recent searches are stored.

- Tabu Search (TS)

  Tabu Search (TS) was initially introduced by Glover (1986) and discussed in Glover (1989) and Glover (1990). The name tabu search comes from the fact that at any stage of the process a list of recent search positions are kept. The entries on these lists are tabu so to avoid going back to previous solutions. The tabu search algorithm is an iterative improvement approach that when a local optimum is reached the procedure will move to a worse position in unexplored regions of the solution space. Tabu search algorithms are explained by Blazewicz (1993), Morton and Pentico (1993), Pinedo (2002) and Brucker (2004). Tabu search has been applied by Franca *et al.* (1996), Passos and Nazareth (2002) and Liu and Ong, 2004).

- Genetic algorithms (GAs)

  Genetic algorithms are more general and abstract than SA and TS, which can be viewed as special cases of genetic algorithms (Pinedo, 2002). When applying GAs, each iterative step generates a number of schedules, whereas SA and TS generate a single schedule for each iteration. GAs simulate the natural evolutionary process. When applied to scheduling, genetic algorithms view possible schedules or sequences as *individuals* or *chromosomes* of a *population.* Each individual (schedule) is characterised by its *fitness* and this is measured by the associated value of the objective function. The procedure is iterative and each iteration that is generated corresponds to a *generation.* The population of a generation consists of new *children* (schedules) and survivors from the previous generation. Children are generated through reproduction and mutation. Advantages and disadvantages of GAs are that they can be applied to a problem without having to know much about the structural properties of the problem. They are easily coded and give fairly good solutions, but the computational time needed can be large compared to other approaches (Pinedo, 2002). Among applications of scheduling problems for genetic algorithms are those by Candido *et al.* (1998), Cardon *et al.* (2000) and Cheung and Zhou (2001).

(g) Disjunctive programming and disjunctive graph model

The disjunctive graph model provides a good technique for representing job shop problems. The elements included in the design of a disjunctive graph are of the from **G = (V, C, D)**, (Blazewicz, 1993, Pinedo, 2002 and Brucker, 2004) where;

- **V** is the set of nodes that represent the operations of all jobs. There is also a *source* node and a *sink* node (start and stop nodes). The weights of the nodes represent the processing times of the operations. The source and sink node have weights 0.
- **C** is the set of directed *conjunctive* (joining, connective or solid) arcs that represent the routes of the jobs.
- **D** is the set of *disjunctive* (separated, divided or broken) arcs. Two operations that belong to two different jobs and that have to be processed on the same machine are connected to one another by disjunctive arcs.

The makespan of a feasible schedule is determined by the longest path in G(S), starting at the source and terminating at the sink. Therefore, to minimise the makespan the disjunctive arcs that minimise the longest path, minmise the makespan. This is referred to as the *critical path* (Pinedo, 2002). Figure 2.10 shows an example of disjunctive graph (Blazewicz, 1993), with the information displayed in Table 2.11. They show two jobs that need processing on three different machines. Table 2.11 illustrates that both jobs go through all machines, with Job 1 being processed in the order Machine 1, Machine 2 and Machine 3, while Job 2 is processed in the order Machine 1, Machine 3 and Machine 2.

Job Number	**Machine number / Process time (P)**	**Machine number / Process time (P)**	**Machine number / Process time (P)**
Job 1	Machine 1 / P = 3	*Machine 2* / P = 1	Machine 3 / P = 3
Job 2	Machine 1 / P = 2	Machine 3 / P = 2	*Machine 2* / P = 1

Table 2.11: Job data for disjunctive graph example in Figure 2.10.

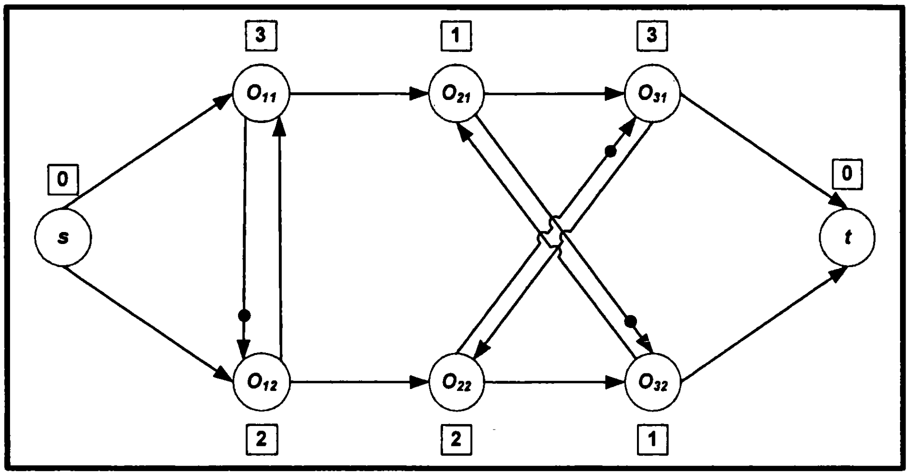


Figure 2.11: Example of disjunctive graph.

In Figure 2.11, O depicts an operation and does not represent the machine, which is denoted by M in Table 2.11. Hence O_{22} is the second operation for the second job and this takes place on machine 3. The critical path (longest) in the disjunctive graph is given by the arcs (s, O_{11}), (O_{11}, O_{12}), (T_{12}, T_{22}), (T_{22}, T_{31}) and (T_{31}, t). The critical path is displayed as a schedule in Figure 2.12.

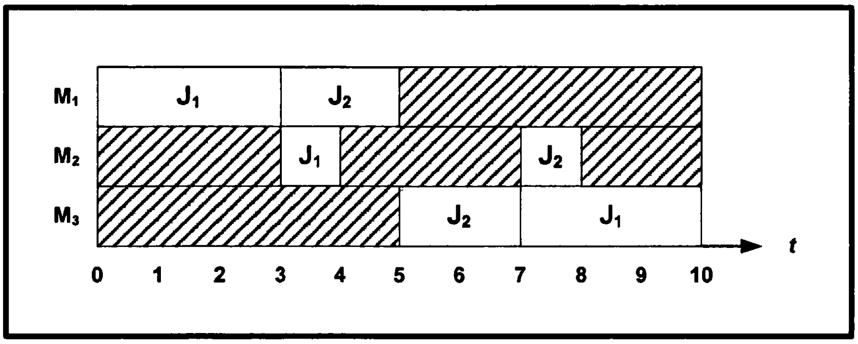


Figure 2.12: Schedule of critical path from disjunctive graph.

Other examples of the use of disjunctive graphs have been described by Raimond (1969), Lageweg *et al.* (1977), Candido *et al.* (1998), and Xu (2001).

The disjunctive programming formulation is closely related to the disjunctive graph representation of the job shop. Constraints can be divided into a set of conjunctive constraints and one or more sets of disjunctive constraints. A set of constraints is called conjunctive if each one of the constraints has to be satisfied. A set is disjunctive if at least one constraint has to be satisfied, but not necessarily all. In a standard linear program all constraints are conjunctive. Blazewicz

(1993), Pinedo (2002) and Brucker (2004) all give thorough explanations of the application of branch and bound to disjunctive programming.

(h) Agent-based scheduling approaches

The design of intelligent agents (or intelligent software agents) is part of artificial intelligence (AI) research. A software agent is an abstraction, a mental model that describes software that acts for a user or other program in a relationship of agency (Wikipedia The Free Encyclopedia, 2006a). There are also different types of agents, for example;

- *Autonomous agents* that can adapt the way in which they achieve their objectives.
- *Distributed agents* would be executed on physically distinct machines.
- *Multi-agents* do not have the capacity to achieve an objective alone and must communicate and collaborate with other agents.

In a scheduling problem when applying agents it is common to use *market agents* to represent jobs and machines in a manufacturing environment. The job agents (or buyers) will negotiate with machines agents (or sellers). A job agent will request a bid from machine agents, they will respond by sending out quotations. Market based agents that negotiate with one another have been applied to scheduling by Pinedo (2002) and Lei *et al.* (2002).

Lu and Yih (2001) have outlined a framework for agent-based production control where they have applied autonomous agents. They have studied a multi-line elevator manufacturing facility. They use four different types of agents (cell agent, sub-assembly agent, order agent and line agent) that hold different information. For example the sub-assembly agents hold order number, type, remaining process time etc. The order agents hold order number, list of sub-assemblies, slack time for all sub-assemblies etc. The different agents communicate with each other similar as outlined in Figure 2.13 with the cell agents determining the priority of sub-assembly according to slack time and machine status.

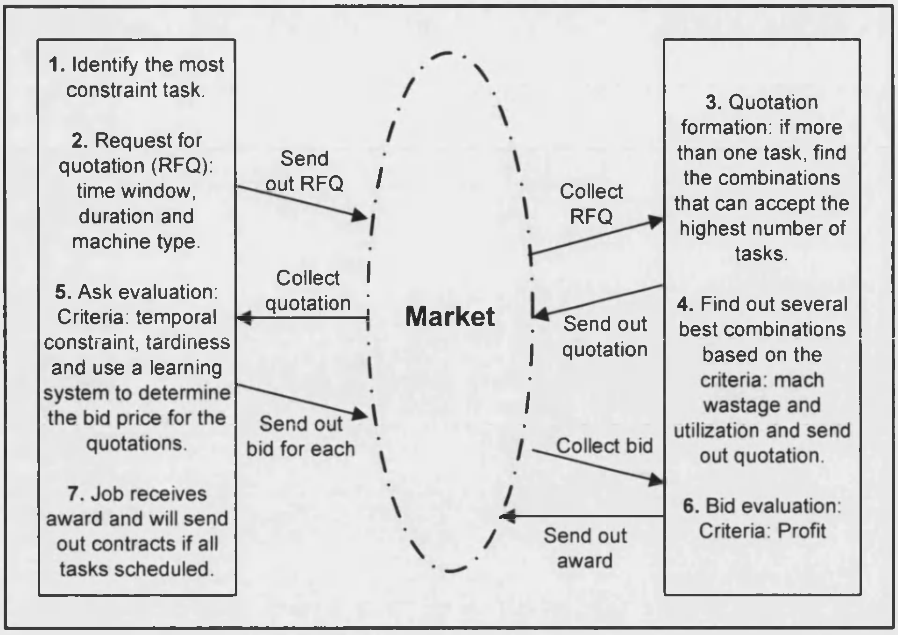


Figure 2.13: Example of negotiation process for market agents adapted (Lei *et al.*, 2002).

Another example of an agent-based scheduling approach is a multi-agent approach with a distributed ruler strategy (Wang el al., 2003). Agents communicate as explained earlier and the ruler-based decision making mechanism are included in the agents to resolve cooperation or conflicts. Examples of rules are the *calculate-ruler* and the *evaluate-ruler*. Agents will also take decisions according to the systems global performance. Similar to the approach by Lu and Yih (2001), Wang el al. (2003) have different classes of agents, such as management agents, resource agents and part agents. An example of a bid-ruler for a resource agent could be “IF some new task announcement message is received THEN make a bid”. Wang el al. (2003) applied their agent-based scheduling approach to a simulation of a machine tool workshop and ran simulations with five different dispatching rules. The shortest process time rule (SPT) showed the best result.

(i) Decomposition methods

The general procedure of decomposition methods is that a schedule is first determined for all machines up to a given point in time, ignoring everything that could happen afterwards. Thereafter a schedule is generated for the next time period and so on. In practice, decomposition methods are often combined with other methods, such as local search procedures.

Four types of decomposition methods are described here.

- Machine-based decomposition

  Machine-based decomposition is often applied to flow, job and open shop environments. Scheduling is performed one machine at a time starting with the one that is most difficult to schedule, the second most difficult etc. The *control structure*, determines which sub-problem needs to be solved and when. An example of this method is the *shifting bottleneck technique*. Pinedo (2002) gives some examples of this approach with the objective of makespan and the objective of total weighted tardiness.

- Job-based decomposition

  For the *job-based decomposition* method a sub-problem consists of all the operations associated with a particular job. Jobs are prioritised and inserted in the schedule one at a time. If an insertion of a new job is not feasible the jobs inserted before have to be rescheduled.

- Time-based decomposition

  The *time-based decomposition* or *Rolling Horizon Procedure* (RHP) can be applied in any machine environment. There are different types of decomposition for this method:

  - Decomposition by time intervals of the fixed length and the iterations only considers jobs released during a particular interval.
  - Decomposition is considered when a list of jobs is released consecutively.
  - There are also more “natural” decomposing forms. Say for instance that at a certain point, a machine is idle and no jobs are waiting, then this can be a natural partitioning point.

  Pinedo (2002) supplies a couple of examples that use time-based decomposition. The Rolling Horizon Procedure (RHP) has been compared to the dispatching rule, Earliest Due Date (EDD) (section 3.3) and EDD-LI, which is the EDD rule coupled by a local search procedure (Ovacik and Uzsoy, 1994). The RHP outperforms EDD and EDD-LI for a single machine scheduling problem.

- Hybrid decomposition methods

  Hybrid decomposition methods a fourth class of these procedures combine either machine- or job-based decomposition with time-based decomposition.

(j) Bottleneck methods

A bottleneck is an operation or machine that limits the output in the production sequence (Heizer and Render, 2000). Bottlenecks have less capacity than the prior or following work centres. *The boy-scout analogy* in chapter 13-15 in Goldratt and Cox (1993) provides an entertaining description of the dynamics of bottlenecks and gives ideas on how to deal with them. Bottlenecks are often studied for scheduling problems, because their characteristics can constrain the whole production system. Techniques for dealing with bottlenecks include; increasing capacity of the constraint, well-trained and cross-trained operators, alternative routings, inspecting before the bottleneck so that faulty products are not going through (Heizer and Render, 2000). With regard to scheduling one suggestion is to schedule throughput to match the capacity of the bottleneck.

Bottleneck dynamics is an advanced dispatch scheduling technique, a heuristic dispatch scheduling that dynamically forecasts due date problems and critical resources. This can be used to estimate delay cost in terms of processes (Morton and Pentico, 1993). The bottleneck resource is identified and prioritises are set in the rest of the system in relation to the bottleneck. Pinedo (2002) applies *the shifting bottleneck heuristic* to deterministic job shops with makespan and total weighted tardiness criteria. This procedure considers a group of machines in terms of a single machine. After solving all these single machine problems, the machine with the largest maximum lateness is chosen, and this is the "bottleneck". The schedule then focuses on the optimal solution obtained for the single machine problem associated with this machine. Thereafter, all machines scheduled earlier are re-sequenced. This is an iterative process.

(k) Theory of constraints

Theory Of Constraints (TOC) is *"that body of knowledge that deals with anything that limits an organization's ability to achieve its goals"* (Heizer and Render, 2000). It is important to identify the operations that constrain output, because it is the throughput, i.e. units processed through the facilities and sold, which are usually the key drivers. Constraints can be physical, for example machines, raw materials, supply or non-physical for example procedures and training. Goldratt (1990) recognises a five-step procedure to understand and asses these constraints.

1. Identify the system's constraints.
2. Decide how to exploit the system's constraints.
3. Subordinate everything else to the above decision.
4. Elevate the systems constraints.
5. If in the previous steps a constraint has been broken, go back to step 1.

The theory of constraints has been used by researchers such as Qiu *et al.*, (2002) for scheduling a yarn manufacturing environment.

(l) Dispatching rules

Dispatching or priority rules are scheduling heuristics commonly used for scheduling problems where no optimal solution algorithm exists. Dispatching rules determine the sequence of jobs in process oriented facilities (Heizer and Render, 2000). Dispatching rules are discussed in detail with emphasis on changeovers in section 3.3.

Dispatching priority rules

A form of heuristics is so called *priority rules* or *dispatching rules*. For scheduling problems where no optimal solution algorithm exists, the use of these rules is common. These rules try to minimise completion time, number of jobs in the system and job lateness, whilst maximising facility utilisation. Heizer and Render (2000) defines this heuristic as *"rules that are used to determine the sequence of jobs in process oriented facilities"*.

It has to be said that in the naming of this group of heuristics in the literature there is some inconsistency. To avoid confusion, it is important to clarify that the many different names that exist represent the same type of heuristic rules.

"The way a machine selects the job to be processed next from the set of waiting jobs is called priority, scheduling or dispatching rule" (Holthaus and Ziegler, 1997). Heizer and Render (2000) call these rules *priority rules* and explain that they are used to determine the sequence of jobs in process-oriented facilities. Morton and Pentico (1993) use the term *dispatch rule*. Baker (1974) prefers the name *dispatching rule* while Rànky (1986) uses the term *scheduling rule*. Perhaps the different designations of these rules show the interest and usefulness of these scheduling heuristics and

indicate their importance. As the proverb says "a beloved child has many names". Examples of priority rules are Shortest Process Time (SPT), First Come First Served (FCFS) and Earliest Due Date (EDD). These will be described in full further on. The use of priority rules, the different types, and their application is reviewed in depth in section 3.3.

2.6.4 Clarification of mathematical programming models and algorithms

There is some discrepancy in the classifications of the above described algorithms. For instance Pinedo (2002) classifies SA, ST and GAs as *local search procedures* and explains that local search procedures do not guarantee an optimal solution, but attempt to find a better schedule in the *neighbourhood* of the current one. Brucker (2004) supports this view stating that SA and ST are *local search heuristics* and emphasize that the quality of local search heuristics strongly depends on the neighbourhood used.

Pinedo (2002) compares local search procedures according to four criteria:

(i) The schedule representation needed for the procedure.
(ii) The neighbourhood design.
(iii) The search process within the neighbourhood.
(iv) The acceptance-rejection criterion.

When Pinedo (2002) and Brucker (2004) talk about neighbourhood design, the neighbourhood search approach (Morton and Pentico, 1993) is not the focus of their discussion. When using a search technique to systematically search for new schedules, the possible moves from one solution to the next need to be restricted in some way. This restricted "search area" is called neighbourhood. *"Two schedules are neighbours if one can be obtained through a well-defined modification of the other"* (Pinedo 2002).

Liu and Ong (2004) prefer to define SA, ST and TA as metaheuristics. Morton and Pentico (1993) divide algorithms in older and newer approaches respectively, where SA, TA and GAs belong to the group of newer approaches. They also discuss the algorithms from the point of view of whether they are *intensifying*, *diversifying* or both, which they call a *mixed strategy*. According to these deviations the following conclusion can be made.

Neighbourhood search is a pure intensifying search, while random sampling is purely diversifying. The branch-and-bound approach and dynamic programming will search for an optimal solution and can because of this incur unacceptable running times. However, it should be noted that because of modern computers running times are being reduced. The current definition of Moore's Law is that data density has doubled approximately every 18 months. Most experts, including Moore himself, expect Moore's Law to hold for at least another two decades (Webopedia, 2004) and Intel Corporation (2005). Beam search takes a step from branch-and-bound and diversification, when applying a beam width of the search. Tabu search explores similar areas as beam search as it takes a step from no diversification to towards diversification. Simulated annealing and genetic algorithms are combinations of intensification and diversification approaches.

2.6 SCHEDULING SOFTWARE

This section gives an overview of the types of scheduling software and systems that are commercially available for planning and scheduling activities. For information on functionality that those systems offer, Wikipeida (2006) was consulted.

2.6.1 Overview of scheduling software

There is a range of software packages on the market that deal with scheduling. Certain software is specifically developed for scheduling of manufacturing processes and businesses may have developed their own user defined software. There is also software, such as Enterprise Resource Planning (ERP) (Wikipeida, 2006) systems that incorporate scheduling as one of the modules. ERP systems integrate (or attempt to integrate) all data and processes of an organization into a single unified system. Prior to ERP systems, Material Requirements Planning (MRP) (Browne, *et al.*, 1996) systems were commonly applied, and still are. An MRP system ensures that materials and products are available for production and delivery to customer, it maintains the lowest possible level of inventory and plans manufacturing activities, including scheduling. Where the Master Production Schedule (MPS) provides knowledge of the end item being created (i.e. Bill of Material (BOM)), quantity required at a time and when this quantity is required to meet the demand. MRP can be a part of Manufacturing Resource Planning (MRP II), which address more areas than MRP and can incorporate business planning, sales and operations planning, production planning, master scheduling, MRP and capacity requirements planning.

In the scheduling literature examples of applying Expert Systems (ES) to scheduling problems have been found. An Expert System is in essence a knowledge-based system, a computer program that contains some subject-specific knowledge of one or more human experts. The system uses this knowledge combined with rules and reasoning capabilities to reach conclusions. For example, Abdallah (1995) has simulated a job shop applying a knowledge-based system. Features of a realistic environment such as, need to change due dates, rescheduling, maintenance and breakdowns have been incorporated. Li *et al.* (2000) have applied an expert simulation system for studying rescheduling of a job shop problem.

Software for Artificial Intelligence (AI) has also been applied to scheduling problems. AI is a branch of computer science that deals with intelligent behaviour, learning and adoption in machines. AI software may be based on agent-based approaches (described in section 2.6.3(b)). Atabakhsh (1991) has reviewed AI techniques applied in constraint based scheduling. Metaxiotis *et al.* (2003) proposes a AI-based production scheduling approach that could be incorporated as a custom module in an ERP system. Chan and Chan (2004) have surveyed future trends of Flexible Manufacturing Systems (FMS) and conclude that they foresee that AI approaches will be dominant in the future.

Furthermore, software for discrete event simulation, for example Witness, which is applied in this research, may be used for scheduling and sequencing activities. The advantage with a discrete event simulation approach is that a range of scheduling scenarios can be tested and it also offers visibility of for example buffer queues. However, it may be time consuming to build the simulation model. Lacomme *et al.* (2005) have coupled a heuristic branch-and-bound scheduling approach with a discrete events simulation model.

Even if no specific software is applied for scheduling and production planning, scheduling may be performed manually with the assistance of such software as Microsoft Excel.

2.6.2 Examples of commercial scheduling software

This section briefly outlines common scheduling software and packages available on the market. Which planning and scheduling system to use depends on each company's need and the software incorporated in this section is a selection of available packages. Should a company wish to implement a scheduling system, an extensive and in-depth survey would be needed to find the appropriate solution.

Probably one of the most well known ERP systems is the one by SAP AG (Systems, Applications and Products in Data Processing Ltd) (SAP, 2006). SAP provides a range of enterprise software applications and business solutions. The mySAP ERP includes among others features such as, procurement monitoring, manufacturing reporting, quality management and sales planning. PeopleSoft EnterpriseOne is another ERP product. Originally it was developed by J.D. Edwards. However, J.D. Edwards was acquired by PeopleSoft, Inc. and the ERP software was renamed PeopleSoft EnterpriseOne. Later PeopleSoft, Inc. was taken over by Oracle Corporation, that currently sells PeopleSoft EnterpriseOne (Wikipedia The Free Encyclopedia, 2006c). Glovia is another company that provides ERP solutions for manufacturing, one of their modules is an MPS module and furthermore the Glovia package considers supply chain management (Glovia, 2006).

Finite Capacity Scheduling (FCS) is defined as scheduling that recognises the actual factory work centre capacity limits (Jobtime, 2006). Advanced Planning and Scheduling (APS) extends FCS by adding additional features such as recognising material constraints and supply chain support (Jobtime, 2006). Preactor International Ltd offers a FCS and an APS scheduling tool (Preactor, 2006). The Preactor production scheduling system provides the planner with an interactive decision support tool that helps balance demand and capacity. Barnett *et al.* (2004) have extended the Preactor scheduling software with a new scheduling system called 3S (Shoe Scheduling System), which is a two-level planning approach consisting of a global (factory) level and a local (team based) level. The Sage MAS 500, is an APS software provided by The Sage Group plc (Sage Software, 2006). The Sage MAS 500 manages production using advanced scheduling rules and incorporates a simple drag-and-drop schedule board.

A number of discrete event simulation software packages exist. An example is Witness provided by Lanner Group, Inc. (Lanner, 2006). The advantages with Witness are that it has a simple but powerful building block design, uses a sophisticated graphical display and is extremely interactive. The graphical display is useful for validation and verification purposes and assists the comprehension of the models. Other discrete event simulation software includes; SIMUL8, provided by SIMUL8 Corporation (SIMUL8, 2006) and Arena, provided by Rockwell Automation, Inc. (Arena, 2006). The SIMUL8 software is user friendly in regard of programming, although it lacks the graphics of the Witness software. Arena is a well known discrete event simulation package, but like the SIMUL8 software its graphical interface is limited and based on flow chart diagrams.

2.6.3 The future of scheduling software

The design of process scheduling and planning systems has been reviewed by Applequist et at. (1997). Applequist et at. (1997) emphasise that there is a wide array of technology for solving scheduling problems, but they believe that market pressures will favour those technologies that can support increased modelling realistic industrial scheduling and large size problems.

When it comes to systems development and integration Pinedo (2002) foresees;

- That *distributed scheduling* will become more important. This means that instead of performing scheduling on just a single workstation. The computational effort may be divided over a number of workstations or computers.
- That *user interfaces and interactive optimisation* will develop to improved interactive optimisation, possibility to zoom in and out and automatic feasibility re-scheduling function after user interaction.
- Wider use of *scheduling description languages*, which enables the scheduler to write the code for a complex algorithm with only a limited number of concise statements. For example, the input from a tabu-search may be; a set of jobs, machine environment, processing constraints, length of tabu-list, initial schedule and maximum number of iterations.
- That scheduling software for manufacturing would be *integrated with other supply chain management modules*, such as forecasting, demand management and inventory control.

CHAPTER 3 THE RELATIONSHIP BETWEEN SCHEDULING, SEQUENCING AND CHANGEOVERS

3.1 INTRODUCTION

This chapter offers a background into the core work of the research presented in this thesis. The relationship between scheduling and changeovers is described and the concept of changeover in its broader perspective is defined. The impact scheduling decisions have on changeover time is outlined, with a section discussing complexity of scheduling problems incorporating changeover times being included. The discussion then leads on to dispatching rules with emphasis on scheduling rules that are changeover sensitive. Meaning they aim to schedule to reduce changeover time, and hence the overall processing time. Scheduling research incorporating changeover or set-up time is reviewed. Finally, a discussion of what is missing in the area of scheduling and changeover concludes the chapter. This identifies the focus of the research described in this thesis by illustrating the gaps in knowledge and how these are used to identify the author's contribution to research in this area.

3.2 CHANGEOVER AND ITS IMPACT ON SCHEDULING

3.2.1 Introduction and definition of changeover

"A changeover is the complete process of changing between the manufacture of one product to the manufacture of an alternative product – to the point of meeting specified production and quality rates".

The above definition of changeover is supplied by McIntosh *et al.* (1996). The set-up period is the readily defined interval when no manufacture occurs. The run-up period starts when production is commenced again and continues until consistent output at full production capacity is reached. The total elapsed time for a changeover, T_c, is shown in Figure 3.1 and is equal to the run-down period plus the set-up period plus the run-up period."

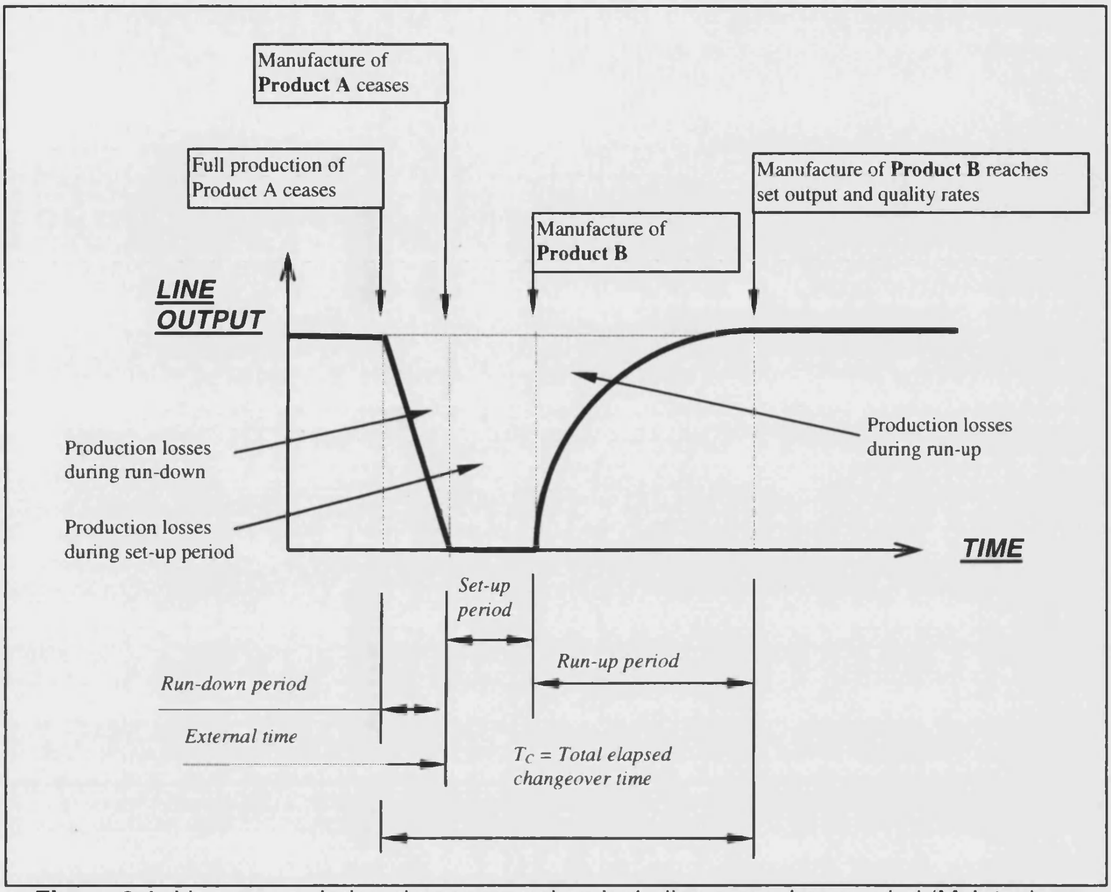


Figure 3.1: Line output during changeover when including a run-down period (McIntosh, *et al.*, 2001).

A *run-down* phase can also be included in the stages as defined by Mileham *et al.* (1999). The three stages are:

- *Run-down* – running the last of the batch through the manufacturing system ready for the new product.
- *Set-up* – this involves removal of the old tooling and equipment and replacing it with the new, followed by a rough-cut setting of the various adjustments required.
- *Run-up* – this involves a series of fine adjustments and checks that are carried out during production until an acceptable quality level and output speed have been reached.

In general in the scheduling and sequencing literature where set-up times are considered, the differentiation between run-down, set-up and run-up is normally not recognised. It is assumed that in general it is the set-up period that is referred to and that run-up and run-down are not incorporated. For example, the Single Minute Exchange of Die (SMED) system developed by Shiego Shingo (1985) does not take this in consideration. Furthermore, the book by Shiego Shingo "A revolution in Manufacturing: The SMED System" does not discuss the issue of changeovers in relation to scheduling, except than mentioning the economic-lot concept. The word changeover is sometimes used, but only to have a meaning directly interchangeable with the word set-up. In fact the literature review for this thesis only revealed one scheduling paper where a dimension of changeover that differs from the set-up phase is taken into consideration. This one paper is written by Gascon and Leachman (1988). They consider that a set-up cost is incurred each time the processing of a job starts, whereas the changeover cost is incurred when the processing switches to that job. For example, if a machine is stopped in the middle of an operation, the set-up cost incurs when production is resumed, but no changeover cost is incurred. Comparing this explanation to the definition by Mileham *et al.* (1999), it seems that what Gascon and Leachman call *set-up cost* is similar to what Mileham *et al.* call the *run-up phase*. Similarly, what Gascon and Leachman names *changeover cost* is equivalent to what Mileham *et al.* explain as the *set-up phase*.

This research has adopted the nomenclature suggested by Mileham *et al.* (1999), which also considers run-down.

The conclusion of this section is that no research was found that considered the run-down, set-up and run-up phases of changeover when scheduling production.

However, within the research concepts related to changeover, and scheduling and sequencing were found to be *sequence dependent set-ups*.
Kim and Bobrowski (1994) explain;

"A sequence dependent setup recognises that the setup time of a job is a function of the preceding job on the machine and therefore the overall sequence".

There are two categories of sequence dependent set-up, lot-sizing and sequencing approach. For lot-sizing the model used by researchers usually is a single machine or a flow shop with a small number of products and the sequencing approach examines sequencing and scheduling decisions as part of a shop floor control system.

The principal measurement for changeovers is *time*. However, it is not uncommon for changeover *cost* to be used. Some authors argue that cost is more appropriate. Normally cost and time are interdependent and the approaches are selected by preference.

Anglani *et al.* (2005) defines set-up within industry as the process of preparing machines or parts for processing.

Jönsson (1999) offers a general definition of set-up time that can also be applied to non-industrial issues as the time taken to prepare for the next task. Interestingly she discusses the occurrence of set-up time in our daily life for every day tasks and explains that set-up time may vary depending on whether the task is easy or hard. Hard jobs often tend to have longer set-up times. *"The challenge is to make a conscious decision to prioritize something hard and work through the set-up time of the task."* Jönsson believes that also concentrated intellectual work demands a set-up time, which may last hours, days, or drag on into weeks and months. Two things can be learned from this; the first one is to realise the need for set-up time, to plan for it and defend it against encroachment. The second is based on the idea of not sub-dividing tasks into too many little bits. A continuous block of time leaves you space to live in. Constantly changing from one task to the other interrupts our thoughts and creates set-up times, which can lower concentration levels and prevent completion of tasks.

The run-up phase also exists in certain intellectual work, for instance, when writing a report or a chapter for a thesis. There is first the set-up, preparation and thinking stage before the writing phase commences. The writing speed may at the beginning be rather slow, but after some time (run-up time) the writing will flow more smoothly and speed of writing will increase until it reaches beyond the run-up period and arrives at a steady state. Although, it has been discussed in this section that many set-ups can break the time up too much and there will hardly be any time left for actual work, it is important to realise the necessity of set-ups taking place, so to avoid interruption as much as possible. In an industrial situation, this could mean that there needs to be a trade-off between say only producing strawberry yogurt and forgetting that vanilla and lemon flavours are tasty and necessary for business too. It is therefore important that changeovers are scheduled to prevent too frequent set-ups, but still meet the market demands for a variety of products and outputs.

3.2.2 The importance and implication of changeover on scheduling

Though it could be argued that set-ups and changeovers should be avoided by for example adopting possible design changes to products, it is inevitable that changeovers to some extent are necessary for most manufacturing processes. In order to reduce the impact changeovers may have on production, scheduling techniques that are sensitive to set-ups and changeovers can be applied. The total time spent on changeover activities depends on the availability of jobs, the job mix, similarities of jobs and scheduling practice applied (Zhou and Egbelu, 1989). For example, if similar jobs are processed in sequence on the same machine, changeover times may be reduced. There are potential savings in changeover time if appropriate scheduling rules are applied Missbauer (1997). The application of adequate scheduling methods will therefore reduce the total changeover time.

Missbauer (1997) has developed an analytical model of the relationship between set-up times and WIP and concludes that WIP can shorten the average flow times, however this can instead increase changeover time and cost.

In many industrial systems set-up times vary depending on the processing sequence of jobs. Examples of manufacturing systems where this is an issue are for instance a job shop where many varieties of products are manufactured and in a continuous manufacturing system, such as a chemical production line, which requires cleaning between batches. The impact of changeover (set-up) on scheduling and sequencing has been discussed in the literature. *Set-up time* is an important element of real production problems, especially *sequence dependent setup times*. In such cases shop performance cannot be effectively improved without appropriate scheduling performance. Kim and Bobrowski, (1994) and Krajewski *et al.* (1987) studied critical factors for improving performance in a manufacturing environment and concluded that the critical factors were lot sizes, *set-up times*, yield losses, workforce flexibility, degree of product customisation, and product structure. Wortman (1992) considered that, queue times that are significantly altered due to work centre bottlenecks, *set-up times that are sequence-dependent* and multiple resource requirements for an operation, are not being addressed adequately in scheduling research. This is emphasised by Gupta (1982) where the cost of set-up is proposed as a criterion to asses the effectiveness of a particular schedule. Kim and Bobrowski (1994) state that for most job shop scheduling research it is assumed that jobs are sequence <u>independent</u>. This is the case despite the knowledge that sequence <u>dependent</u> set-up times are common in industry.

Consideration of set-up times within scheduling use various assumptions (Zhou and Egbelu, 1989) for example;

(I) Set-up times are completely neglected.

(II) Set-up times are sequence independent. In this case set-up times are simplified by being incorporated in the processing times.

(III) Set-up times are sequence-dependent, but separated from the associated job. This means that set-up cannot be initiated unless the job itself is ready for processing.

(IV) Set-up times are sequence-dependent, but separated from the jobs.

Within scheduling research cases (I) or (II) are normally applied, simplifying the problem. In case (IV) where set-up times are sequence dependent little research has been undertaken. Additionally, when set-up times are being considered often real set-up time data is not measured, but minimum, maximum or average set-up time values are estimated.

A couple of examples of schedules, in Gantt chart format, to illustrate the above discussion have been constructed. Table 3.1, Table 3.2 and Table 3.3 are examples of set-up matrices and show set-up times between three jobs on three machines. For Machine 1, it is assumed that the set-up time is the same between jobs also in reverse order, e.g. going from Job 1 to Job 3 gives the same set-up as going from Job 3 to Job 1. For Machine 2 this is not the case. Set-up times for Machine 3 are different,

because here going from a low numbered job e.g. Job 1 to Job 2 or Job 3 does not incur a set-up time, whereas going from a high numbered job to a low numbered job gives a set-up time that also increases with the gap. A practical example of this type of set-up times could be paint production, where the lower the job number would represent lighter colours to be produced. Therefore going from Job 1 (colour white) to Job 2 (colour yellow) to Job 3 (colour black) will not incur set-up time (no cleaning is necessary), but will incur run-up and run-down since the first part of the new colour might be mixed with the previous one and be too light. In this case run-up and run-down times are considered to be dependent more on the machine than on the job. Therefore, run-up and run-down is the same for each job and each machine. The examples use 0.25 units (days) for run-up and run-down on Machine 1, 0.25 units (days) for run-up on and no run-down on Machine 2 and 0.5 units (days) run-up and 0.25 units (days) run-down on Machine 3. The information from the set-up matrices is incorporated in the schedule in Figure 3.2 and Figure 3.3. The schedule in
Figure 3. only includes set-up time, whereas the schedule in Figure 3.3 also include run up and run down. The black colour represents set-up and dark grey represents run-down and run-up. The sum of set-up, run-up and run-down is a full changeover.

	Job 1	Job 2	Job 3
Job 1	0	0.5	1
Job 2	0.5	0	0.5
Job 3	1	0.5	0

Table 3.1: Set-up times for Machine 1.

	Job 1	Job 2	Job 3
Job 1	0	2	2
Job 2	1	0	1
Job 3	1	1	0

Table 3.2: Set-up times for Machine 2.

	Job 1	Job 2	Job 3
Job 1	0	0	0
Job 2	0.5	0	0
Job 3	1	0.5	0

Table 3.3: Set-up times for Machine 3.

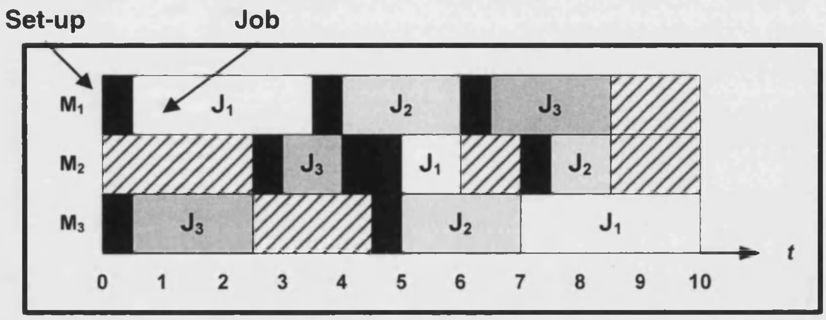


Figure 3.2: Example of schedule including set-up times.

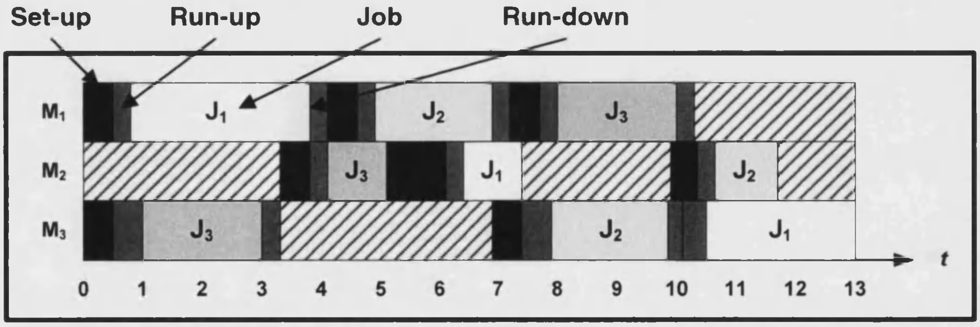


Figure 3.3: Example of schedule including set-up, run-up and run-down times.

3.2.3 Product family, groups of products or product type

Note in the text that follows *product family*, *groups of products* or *product type* imply the same meaning. A product family is where products are grouped with the same characteristic, such as they require the same equipment for set-up. This is an important consideration when aiming to reduce the number of changeovers. Group Technology (GT) is a scheme for parts grouping, machine dedication, and shop arrangement, often reducing material handling and set-up times, decreasing Work-In-Progress (WIP) inventory and giving shorter flow times (Flynn, 1987a, 1987b). Cellular manufacturing is an application of group technology where manufacturing systems have been converted into cells. A manufacturing cell is a cluster of machines or processes dedicated to manufacturing a family of parts (Singh, 1996). Reducing set-up time and batch sizes can reduce lead times. However, additional set-ups may increase the workload, hence there needs to be a trade-off between set-up times and batch sizes. Gung and Steudel (1999) have developed a workload balancing model in conjunction with a heuristic model to determine set-up time reduction schemes for different levels of batch size reduction. Webster and Baker (1995) have reviewed the area of scheduling groups of jobs on a single machine. With regards to scheduling, using product families and GT has been applied by for instance; Ruben *et al.* (1993), Kannan and Lyman (1994), Frazier (1996), Azizoglu and Webster (1997), Qiu and Burch (1997), Webster *et al.* (1998) and Ouenniche and Boctor (2001).

3.2.4 Examples of NP-hard scheduling problems with set-up times

This section discusses the NP-hardness of scheduling problems that considers set-up times. In general, when more detail is added to a scheduling problem the complexity of the problem increases. This is also true when consideration is given to set-up times. The examples given here are scheduling problems that in the literature have had their NP-statues investigated. It is sometimes assumed in the literature that if one problem is NP-hard and a further job characteristic (β) is added to the problem then the more detailed problem will also be NP-hard. Even very restrictive cases of sequencing problems with deadlines and set-up times/costs could be categorised as NP-complete (Bruno and Downey, 1978). Figure 3.4 illustrates that if problems with both variable changeover time (cost) and variable due date requirements are NP-complete. Whereas if changeover time varies and due date setting is constant, scheduling problems are classified as NP-complete, but solvable in pseudo-polynomial time. Problems with equal changeover times and number of task and due dates up to a number of three and problems with variable changeover time and number of task and due dates up to a number of two have also been solved in pseudo-polynomial time. Problems solvable in polynomial time have equal changeover times and number of task up to two and due dates up to three.

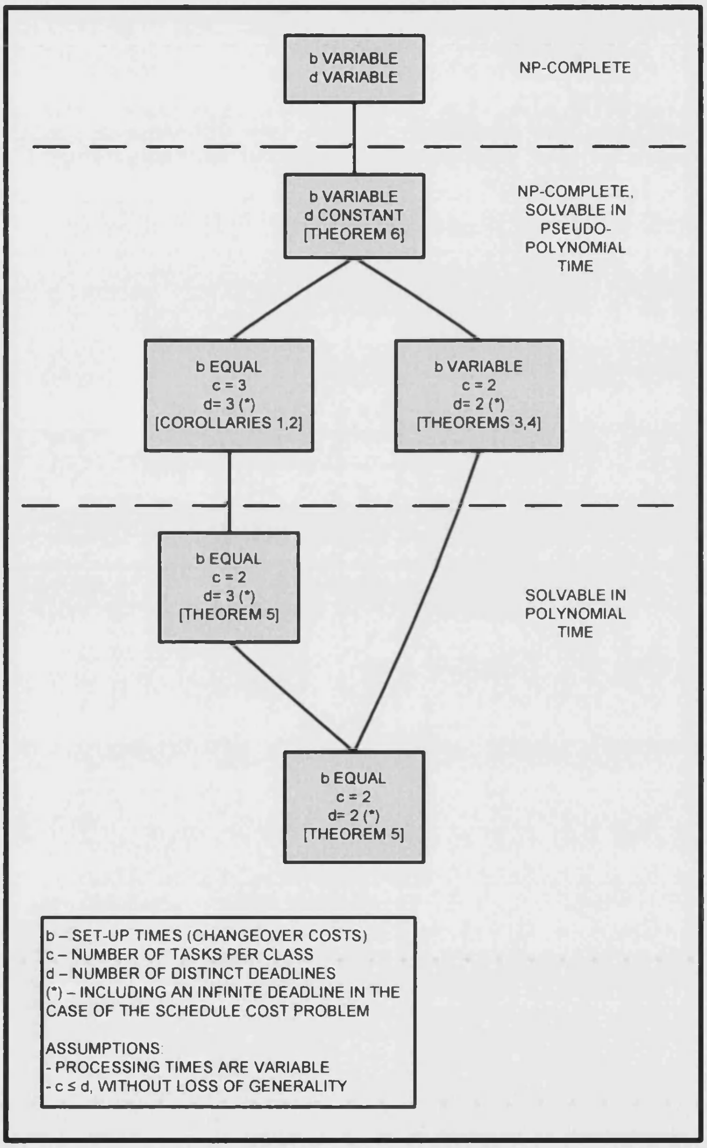


Figure 3.4: NP-hardness for scheduling problems with set-up times and due dates (Bruno and Downey 1978).

Single machine scheduling problems with the performance measures maximum completion time, maximum lateness, total weighted completion time, and number of late jobs *are efficiently solvable* when the number of batches is fixed, even with sequence-dependent set-up times (Monma and Potts, 1989). However, if the number of batches varies, problems with maximum lateness and number of late jobs as criteria are NP-hard, as are those with sequence-independent set-up times. For parallel machine problems with preemption and the performance measures of maximum completion time, maximum lateness, total weighted completion time, and number of late jobs are NP-hard, even if there are only two identical parallel machines, and sequence independent set-up times. That is $(P_2 \mid prmp \mid C_{max})$, $(P_2 \mid prmp \mid L_{max})$, $(P_2 \mid prmp \mid \Sigma w_j C_j)$ and $(P_2 \mid prmp \mid N_T)$ are NP-hard.

The one-operator-two-machine flow shop problem with set-up and dismounting times $(F_2 \mid s_i, \textit{dismount time} \mid C_{max})$ is NP-complete in the strong sense (Cheng *et al.*, 1999). (Note that there is no standard nomenclature for dismounting times.)

The problem of scheduling groups of unit length jobs on two identical parallel machines to minimise the total completion time $(P2 \mid GS \mid C_j)$ is NP-hard. Liu *et al.* (1999) present a pseudopolynomial-time algorithm and establish that the problem is NP-hard in the ordinary sense. Additionally, the problem remains NP-hard even for any case with fixed positive set-up times.

The general job shop problem with arbitrary sequence-dependent set-up times and makespan criteria $(J_m \mid s_{jk} \mid C_{max})$ is NP-complete (Cheung and Zhou, 2001 and Pinedo, 2002).

Even the single machine problem can be NP-hard under certain conditions. Ng *et al.* (2002) have studied the single machine problem with the criteria of minimising the sum of the job completion time. Job characteristic for the problems studied has multi-operation jobs, meaning that each job consists of several operations that belong to different families. Families of jobs may be processed in batches and each batch will incur set-up times. NP-hardness has been shown even for these restricted cases such as $(1 \mid s_f{=}s, \textit{assembly}, p_{(f,j)} = 0 \text{ or } 1 \mid \Sigma C_j)$ and $(1 \mid s_f{=}s, \textit{assembly}, GT, \; p_{(f,j)} = 0 \text{ or } 1 \mid \Sigma C_j)$. However, the authors note that $(1 \mid s_f{=}s, \textit{assembly}, GT, \; p_{(f,j)} > 0 \text{ or } 1 \mid \Sigma C_j)$ is polynomially solvable. This means that when $p_{(f,j)}$ is equal to zero a polynomial-time problem becomes intractable.

Another example is supplied by Dunstall and Wirth (2005a). They have studied the problem of scheduling jobs with family setup on identical parallel machines to minimise the weighted sum of completion times ($P \mid s_i \mid \Sigma wC$). They explain that for the case of a single machine, dynamic programming can solve this problem. However, the computational complexity of this problem with an arbitrary number of job group families remains an open research questions.

3.2.5 Summary

This section has outlined the importance of considering changeover times when performing scheduling. It has also explained that realistically sized scheduling problems where changeover times are present are computationally hard to solve. As discussed earlier for such problems, heuristics rather than exact algorithms are required. The following section presents the use of dispatching rules for scheduling problems and approaches that consider changeover times.

3.3 DISPATCHING PRIORITY HEURISTICS

3.3.1 Definition and characteristics of dispatching priority heuristics

Dispatching or *priority rules* are a form of heuristics. For scheduling problems where no optimal solution algorithm exists, the use of these heuristics is common to determine the sequence of jobs when processing (Heizer and Render, 2000). A priority, scheduling or dispatching rule is a technique to decide which job from a queue of jobs should be selected to be processed next (Holthaus and Ziegler, 1997). Dispatching rules are straightforward to implement and useable in any shop floor configuration, even when dynamic job arrivals are present. Dispatching rules are therefore popular in many real-life manufacturing systems (Jayamohan and Rajendran, 2000).

Characteristics of dispatching rules:

- Dispatching rules can be divided into *local* and *global* dispatching rules (Haupt, 1989 and Holthaus and Ziegler, 1997). Local dispatching rules are rules that only require information about the jobs currently waiting at the machine in question, whereas global dispatching rules are based on information about jobs in other queues or about other machines.
- If the prioritises are calculated in advance, the rule is called a *static dispatch rule*. However, if the sequence choice is made using currently available information, it would be called *dynamic dispatch rule* (Morton and Pentico, 1993).
- An *alternate* rule uses one main rule and will after a certain time change to another rule, so that for instance jobs with long processing time are not waiting too long.
- A *truncated* (tie break) rule uses one rule and when a certain condition is fulfilled another rule takes over (uses a secondary criteria), the first rule is then resumed. FCFS and EDD are often applied as tie break rule. For example Mohanasundaram *et al.* (2002) used FCFS as a tie breaking rule.
- Due date sensitive rules can be *time-independent* and some *time-dependent*. For instance EDD (Earliest Due Date) is time-independent, however CR

(Critical Ratio) incorporates processing time, hence CR is time-dependent (Haupt, 1989).

- There are variants of many dispatching rules such as LS (Least Slack) and LSPO (Least Slack Per Operation).
- Dispatching rules may be combined; for example, Jayamohan and Rajendran (2000) have applied a number of combined rules.
- Popular rules have sometimes been given the different names such as FCFS (First Come First Served) and FIFO (First In First Out), which operates in the same manner.

Concluding the applications of dispatching rules (Subramanian *et al.*, 2000):

- Most common approach in industry.
- Determine the ranking of the order in which jobs waiting at machine queues are to be processed when the machines become available.
- Modified or combined rules to make use of other available information from the job shop floor.

Table 3.4 to 3.8 lists dispatching rules that commonly appear in the scheduling and sequencing literature. Some of the rules are applied in industry. The rules have been divided into five categories;

- Simple dispatching rules.
- Processing time sensitive rules (PSRs).
- Due date sensitive rules (DSRs).
- Rules with global shop information.
- Examples of truncated and combination dispatching rules.

The tables reference where and by whom the rules have been applied and tested or if by whom they have been reviewed. The operation of the rule is explained as well as use and performance of each rule. A total of 21 scheduling rules are included in the tables, plenty more exists, for example Panwalkar and Iskander (1977) have reviewed over 100 scheduling rules. Further reviews have been compiled by Blackstone *et al.* (1982). However, many rules are similar and based on similar principles, other rules may be a combination of rules. The rules included in this section are among the most common ones found both in literature and industry. In the tables a description of the operation of the rule is included, typical use and performance of the rule and reference is gives to researchers that have applied or reviewed each rule. Each table is arranged in alphabetical order according to the name of rule.

Heuristic	Operation of heuristic	Performance of heuristic
FCFS (Blackstone *et al.*, 1982), (Muhlemann *et al.*, 1982), (Haupt, 1989), (Holthaus and Rajendran, 1997), (Holthaus and Ziegler, 1997), (Jeong and Kim, 1998) and (Petroni and Rizzi, 2002)	The First Come First Served rule selects from a queue of waiting parts the one that arrived first and has waited the longest time. Sometimes named First In First Out (FIFO).	In scheduling FCFS is often used as a benchmark rule. It is also often seen when serving people, as it is considered a "fair" rule. Often performs similar to Random rule (Blackstone *et al.*, 1982).
LCFS (Panwalkar and Iskander, 1977)	The Last Come First Served rule selects from a queue of waiting parts the job that arrived last and has waited the shortest time. Sometimes named Last In Last Out (LILO).	This rule is the opposite of FCFS. Hence, LCFS can be used as a validation rule. It is expected that LCFS will perform similar to FCFS, except for meeting due date, where FCFS may have an advantage.
Random (Muhlemann *et al.*, 1982) and (Haupt, 1989)	Selects jobs in a random order, normally according to a random distribution.	Applied as a benchmark rule.

Table 3.4: Simple dispatching heuristics.

Heuristic	Operation of heuristic	Performance of heuristic
LPT (Haupt, 1989)	Longest Processing Time rule selects for processing the job with the longest expected processing time.	Require only operation data, not job data and not data from other queues. LPT is not commonly applied in industry. It has a reputation of not performing well.
SPT (Muhlemann *et al.*, 1982), (Haupt, 1989), (Holthaus and Rajendran, 1997), (Jensen *et al.*, 1995), (Holthaus and (Holthaus and Ziegler, 1997), (Jayamohan and Rajendran, 2000) and (Petroni and Rizzi, 2002)	Shortest Processing Time (SPT) selects the job with the shortest processing time.	SPT is simple to operate and commonly applied as has often showed a worthy performance, for *mean flow time, mean lateness* and *mean tardiness.* Perform well for *number of tardy jobs.* Less sensitive to shop load level variations than slack based rules. Disadvantage is delays of individual jobs.
LWKR (Muhlemann *et al.*, 1982), (Haupt, 1989)	Job with Least Work Remaining is prioritised.	Selects jobs with high fraction of their value added or cumulative value to their total value (value-oriented rule) (Haupt, 1989). Tends to reduce the number of jobs in the shop.
MWKR (Haupt, 1989)	Job with Most Work Remaining is prioritised.	Speeds up jobs with large processing work results in well-balanced work progress, at expense of high volume WIP.

Table 3.5: Processing time sensitive heuristics (PSHs).

Heuristic	Operation of heuristic	Performance of heuristic
CR Time-*dependent* rule (Blackstone *et al.*, 1982), (Muhlemann *et al.*, 1982) and (Haupt, 1989)	Critical Ratio is calculated as the due date less the date now and then divided by the lead time remaining. The job with the lowest CR value is selected.	CR is commonly applied in literature and used in industry. Modifying the EDD rule and including lead time, referring to the *fraction* of a job's allowance and its remaining work.
EDD Time-*independent* rule (Blackstone *et al.*, 1982), (Muhlemann *et al.*, 1982), (Haupt, 1989), (Petroni and Rizzi, 2002) and (Jayamohan and Rajendran, 2000)	Earliest Due Date rule selects the job with the earliest date required to be finished.	This rule is easy to operate. However, it tends to deliver jobs with few operations early and jobs with many operations late. Worthy performance when prioritising *mean tardiness.* Show their best performance under light load conditions.
LS Time-*dependent* rule. (Blackstone *et al.*, 1982), (Haupt, 1989) and (Jeong and Kim, 1998)	Least Slack is calculated as the time remaining to the due-date less the estimated time required for the remaining processes. The job with the least slack is selected.	A commonly applied rule that often shows worthy performance. Modifying the EDD rule and including time, referring to the *difference* of a job's allowance and its remaining work. Perform well according to *tardiness* and *lateness variances.*
LSPO or S/OPN Time-*dependent* rule (Blackstone *et al.*, 1982), (Muhlemann *et al.*, 1982), (Haupt, 1989), (Holthaus and Ziegler, 1997), (Jeong and Kim, 1998) and (Petroni and Rizzi, 2002)	Least Slack Per Operation is calculated as the least slack rule and then divided by the number of remaining operations. The job with the least slack per operation is selected.	Like LS the LSPO rules show a good performance according to *tardiness* and *lateness variances.* Effective when controlling tardiness.
MDD (Jeong and Kim, 1998)	Modification of the EDD rule. Modifies the internal due date of a job to its earliest possible completion time if the job is already late.	Good performance for measure of *mean tardiness.*
MOD (Jensen *et al.*, 1995) (Holthaus and Ziegler, 1997), (Jeong and Kim, 1998) and (Jayamohan and Rajendran, 2000)	The job with the smallest Modified Operation Due date is prioritised. Modified operation due date is the maximum of the operation due date and the earliest possible completion time of the operation.	Good performance for measure of *mean tardiness.*
ODD Time-*independent* rule (Muhlemann *et al.*, 1982), (Haupt, 1989) and (Jayamohan and Rajendran, 2000)	Prioritises a job according to the earliest operation due date	ODD is considered robust and is not affected by routing pattern of jobs, utilisation levels and tightness of due date setting (Jayamohan and Rajendran, 2000).

Table 3.6: Due date sensitive heuristics (DSHs).

Heuristic	Operation of Heuristic	Performance of heuristic
NINQ Global shop information rule. (Haupt, 1989) (Holthaus and Ziegler, 1997)	The least number of jobs in the queue of its next operation. Prioritises jobs which would move to queues with the least backlog, instead of speeding up a job that would be stopped in an overcrowded queue later.	Haupt (1989) and Holthaus and Ziegler (1997) includes the NINQ rule in their reviews. However, they do not discuss its performance.
WINQ Global shop information rule. (Haupt, 1989) (Holthaus and Rajendran, 1997)	The least total work in the queue of its next operation. Prioritises jobs which would move to queues with the least backlog, instead of speeding up a job that would be stopped in an overcrowded queue later.	Can reduce waiting time of jobs. In a study by Holthaus and Rajendran (1997) the WINQ rule performs better than the SPT rule.
COVERT Time-*dependent* rule (Blackstone *et al.*, 1982) (Jensen *et al.*, 1995) (Holthaus and Rajendran, 1997) (Holthaus and Ziegler, 1997) (Jeong and Kim, 1998) (Petroni and Rizzi, 2002)	Cost OVER Time. Jobs are prioritised in descending order of the ratio of a penalty function (that takes into account slack and expected waiting time) over the processing time.	Particularly helpful in optimizing tardiness performances.

Table 3.7: Heuristics with global shop information.

Heuristic	Operation of heuristic	Performance of Heuristic
PT + WINQ (Holthaus and Rajendran, 1997) and (Jayamohan and Rajendran, 2000)	The processing time plus work-content of jobs in the queue of next operation of a job.	Performed well for *mean flow time.* Has been shown to perform better than only WINQ and SPT, so consequently a fair trade-off (Holthaus and Rajendran, 1997). Fairly good performance for percentage of tardy jobs (Jayamohan and Rajendran, 2000).
PT + WINQ + LS (Holthaus and Rajendran, 1997) and (Jayamohan and Rajendran, 2000)	Like PT + WINQ, but also considers slack and therefore due date.	Performs well when utilisation of the shop floor is high (Holthaus and Rajendran, 1997). Good for minimising *mean, max and variance of tardiness,* (Jayamohan and Rajendran, 2000).
SPT + alternate FCFS *Alternated rule* (Blackstone *et al.*, 1982)	Uses SPT, however in order to avoid jobs waiting for too long SPT is replaced by FCFS. When the queue of "long-waited" jobs is reduced, SPT is resumed.	This tie break rule prioritises according to SPT, however after a certain number of jobs or certain time FCFS overrule SPT, to avoid jobs with long processing times to become late. It then alternates back to SPT etc.
SPT-T *Truncated rule* (Blackstone *et al.*, 1982)	Jobs are scheduled according to SPT. However, with a restriction e.g. jobs will have to wait for a certain time in the queue before being dispatched.	A truncated SPT rule, has the advantages of SPT, but overcome late jobs that are stuck in the queue because they have very long processing times.

Table 3.8: Example of combination of heuristics.

3.3.2 Discussion and summary of dispatching priority heuristics

Dispatching rules are often efficient and simple to apply to scheduling problems and are especially effective for large complex problems where exact algorithms are not available. A large range of different dispatching rules exists that require different job or processing data to execute. For instance, some rules consider due dates, others processing time or number of operations. It is also common to include for example both due dates and processing time, such as the CR rule. Rules with a good reputation for performing well are SPT and slack based rules such as LS and CR. However, among the common scheduling rules previously discussed no rule prioritises reduction of changeover time. There are due date sensitive rules (DSRs) and processing time sensitive rules (PSR), but no changeover time sensitive rules (CSRs). Despite changeover (set-up) time being considered important in scheduling decisions (section 3.4) and the fact that changeover (set-up) times are frequently present in scheduling problems, they are rarely incorporated in the dispatching rules. However, examples of changeover time sensitive rules (CSRs) have been found in the literature and those are discussed in the next section.

3.4 CHANGEOVER SENSITIVE HEURISTICS

3.4.1 Definition of changeover sensitive heuristics

Set-up, changeover times and cost and their relationship to scheduling have regularly been addressed in the scheduling literature. A comprehensive review, of scheduling and set-up (changeover) issues, is provided by, Allahverdi *et al.* (1999). The relationship between scheduling and group technology have been reviewed in, Mosier and Taube (1985) and Mahmoodi and Dooley (1992). Despite that set-up times have been included in many studies of scheduling and sequencing rules, it is less common to attempt to schedule according to reducing set-up time. Meaning set-up times may be included simply as an addition to the processing times. *Sequence dependent set-up times* (changeover times) and their impact are of interest to this particular research topic as they recognise that the set-up time of a job is a function of the preceding job on the machine and therefore the overall sequence (Kim and Bobrowski, 1994). These relationships however are not typically used in the formation of common priority rules e.g. the FCFS. A more unconventional group of priority rules which are set-up-conscious recognise the sequence-dependent nature of set-up (changeover) time and consider the set-up (changeover) requirements of jobs during sequencing. Meaning, if a changeover takes place between two identical jobs which also have identical changeover, the changeover time would most probably be reduced if those products were scheduled in sequence (Kim and Bobrowski, 1997). This indicates that the total time to complete a job (process time and changeover time) could be reduced, should changeover implications be considered when scheduling is performed. For the research presented in this thesis, rules which take account of changeover are referred to as Changeover Sensitive Heuristics (CSHs).

Mahmoodi *et al.* (1992) refers to changeover sensitive heuristics as *group scheduling* and they differentiate between the definitions *of single-stage traditional heuristics* and *two-stage group scheduling heuristics*. Where the first stage sorts jobs within a sub-family according to for example FCFS and the next stage determines the order in which to process the sub-families. Mosier *et al.* (1984) outline group scheduling heuristic as necessary of three decisions;

(a) The decision *when* a new queue of jobs should be selected.

(b) The decision *which queue* of the two remaining queues to select (Mosier *et al.*, (1984) only studies three sub-families all belonging to the same product family).

(c) The decision *which job* to select from the chosen queue.

The definitions by Mosier *et al.* (1984) and Mahmoodi *et al.* (1992) imply that jobs have already been arranged in sub-family queues when the sequencing process starts. Meaning in front of the first processors there will be e.g. three queues of different sub-families to choose from. Those sub-families all belong to the same product families. This assumption is common in other studies, for example, (Mahmoodi *et al.*, 1990), (Mahmoodi and Dooley, 1991), (Mahmoodi and Dooley, 1992), (Ruben *et al.*, 1993) and (Mahmoodi and Martin, 1997).

3.4.2 Sequence-dependent set-up research where changeover sensitive heuristics are not present

Research into sequence-depended set-up time and scheduling has taken place also without investigating the impact of changeover sensitive heuristics (CSHs). Instead other methods to solve sequence-dependent set-up problems have been applied. The focus of the research in this thesis lies on the impact of CSHs. However, this section gives and overview of other approaches divided into categories named *borderline rules heuristics*, *range of solutions* and *optimal* solutions.

<u>Borderline heuristics</u>

When studying the literature, scheduling heuristics that do not fully qualify as CSHs have been found. However, they have elements of CSHs in them; hence they fall into the category of *borderline heuristics.*

For example, Kurz and Askin (2004) compares four heuristics for a problem of minimising makespan in flexible flow lines. In this research the sequence-dependent set-up times are not explicitly studied, but they are accounted for by integrating their values into the processing times. The first heuristic is a variation of the SPT rule, SPT Cyclic Heuristic (SPTCH). Next an insertion heuristic (FTMIH) is suggested. FTMIH places jobs in order of LPT onto the machine, the true sum (real value of processing and set-up time, rather than modified processing time) of flowtime is calculated and job i is placed in the position on the machine with the lowest resultant sum of flowtimes. The third rule "g/2, g/2" is a modification of Johnson's Rule that incorporates the modified processing times that include set-up times. The fourth heuristic was a Random Keys Genetic Algorithm (RKGA), where random numbers were used as sort keys in order to decode the solution. Kurz and Askin (2004) concludes that their genetic algorithm RKGA performed best.

Kurz and Askin (2003) have also tested SPTCH, FTMIH and "g/2, g/2" against a simpler version of "g/2, g/2" named "1,g" where the modified processing time is only applied for stage 1 of the flow shop. "g/2, g/2" includes modified processing times also at other stages. This study also tested another two rules Cyclic Heuristic (CH), which arranges jobs in numerical order and assigns them to machines in cyclic order, and Ready Time Cyclic Heuristic (RCH), which is similar to CH, but at the second stage of the flow shop and onwards, jobs are sequenced in increasing order of ready times. This study showed that the Johnson's Rule-based heuristics performed well.

Davies and Kanet (1997) have developed an interactive computer graphics approach to scheduling, whereby the schedule can be modified by "drag and drop" functions or by inbuilt routines that automatically re-schedule. By moving jobs so that jobs that require the same or similar set-ups are scheduled in sequence changeover time can be reduced.

Range of solutions

Furthermore, there are other approaches that are not necessarily changeover sensitive, but consider sequence dependent changeover times. Many approaches belong to what here is referred to as *range of solutions*. This means that rather than emphasis on scheduling similar jobs in sequence, range rules test a large range of schedules and eventually stop on a schedule that minimise the performance criteria chosen. This way changeover time might have been reduced through testing a number of possible schedule and settle on a satisfying result instead of directly scheduling with changeover time in mind.

Tan and Narasimhan (1997) have applied a Simulated Annealing (SA) approach to the single machine problem with the objective of minimising tardiness and accounted for sequence-dependent set-up times. The SA approach generated a range of schedules and the authors show that for the 10-job cases optimum solutions can be found in just over 50% of the cases. For the 30-job and 50-job problems optimum solutions were not available and instead a "good enough" solution will exist among a range of possible solutions.

The study by Rajendran and Ziegler (2003) aim to minimise the sum of weighted flowtime and weighted tardiness of jobs in a flowshop with sequence-dependent set-up times. The authors have developed one heuristics that attempts to schedule the jobs with the smaller processing and set-up times and larger holding and tardiness costs ahead of jobs with larger processing and set-up times and smaller holding and tardiness costs. The second heuristic sequence jobs with an early due-date and with large weights for holding and tardiness ahead of jobs with a late due-date and with small weights for holding and tardiness. Both heuristics are applied and the one that generates the better sequence with respect to the objectives is chosen. An improvement scheme is thereafter applied to this sequence, whereby jobs are moved around to different positions within the sequence so that a possible better solution can be found. Hence, a range of solutions are tested. The heuristic shows a worthy performance compared to three benchmark procedures.

A Tabu Search (TS) algorithm for independent jobs with sequence-dependent set-up times on uniform parallel machines with total tardiness as performance measure has been developed by Bilge *et al.* (2004). The number of jobs tested is 20, 40 and 60 and the number of machines has been tested for 2 machines and 4 machines. Both an intensification and a diversification strategy of the TS have been applied and both improve the TS solution. The tabu search method has also been applied by Logendran *et al.* (2006) for a flexible flowshop scheduling problem with sequence-dependent set-up times. Furthermore, Choobineh *et al.* (in press) have applied tabu search to a single machine problem with sequence-dependent set-ups.

Gupta and Smith (in press) have also studied the single machine problem with sequence-dependent set-up times and they apply a local search heuristic as well as a Greedy Randomised Adaptive Search Procedure (GRASP). The algorithms are compared to simulated annealing, genetic search, pairwise interchange, branch and bound and ant colony search and the authors show that their algorithms perform very competitively.

This section has given examples of some of the approaches for scheduling within the category defined as range. This is a category where many different approaches are applied. As has been outlined above, approaches include for example Simulated Anneling and Tabu Search techniques.

Optimal solutions

There are also a couple of examples of *optimal* solutions where sequence dependent changeover times are included. Those approaches are also discussed. However, due to NP-complexity, optimal solutions can only be found for a limited number of jobs and machines.

Hitomi and Ham (1976) analysed a five-stage manufacturing operation and they developed a branch and bound algorithm and showed that they could obtain the optimal solution for minimising total flow time (makespan) when scheduling 14 jobs belonging to 4 groups (families). Hitomi and Ham continue their research (1977), where they add the experimental factor of machining speed. They determine also the optimal machining speed to reduce the total production cost as well as minimising makspan. They also applied the optimal machining speed to investigate its performance with due-date constraints (1979). Again optimisation algorithms that determine optimal group schedules and machining speeds are proposed. The objectives of their algorithms were to minimise makespan and the number of tardy jobs. A numerical example is included in their research containing 7 jobs belonging to 3 groups (families) scheduled on four stages (operations). They have also addressed the problem of developing optimal machine loading and product-mix decisions (1978). In this study the principles were tested on a single machine and a computational algorithm was developed. With regard to set-up the approaches by Hitomi and Ham involve sequence independent set-up times and not sequence-dependent set-up times.

Ozden *et al.* (1985) propose a dynamic programming-based formulation, applied to a single machine problem with sequence-dependent set-up times and the objective of minimising total set-up time. They show that they can find an optimal solution for a maximum of 29 jobs belonging to 4 groups.

Haase and Kimms (2000) have studied the single machine problem where set-up time and costs are sequence dependent. They applied a brand-and-bound method to find optimal solutions to problem sizes ranging from 3 jobs and 15 time periods to 10 jobs and 3 time periods. The authors claim that this has practical relevance in certain industrial settings i.e. food industry, where instances with less than 10 jobs occur. It can however be argued that in many environments 10 jobs is a very low number.

Méndez *et al.* (2001) suggests a Mixed-Integer Linear Programming (MILP) mathematical formulation for a flowshop scheduling problem with sequence-dependent set-up times. Their objective was to minimise the total order earliness. Three examples for a five-stage flow shop with five orders each are include and optimal solutions for those are given.

In summary despite the advances in techniques and scheduling approaches over the last 30 years, the number of jobs scheduled optimally in the above examples is still low. The low number of jobs and processors scheduled optimally indicates that heuristic alternative approaches to sequencing and scheduling should still be emphasised.

3.4.3 Applications of changeover sensitive heuristics

This section describes changeover sensitive heuristics (CSHs). There is a range of different CSHs, although many are based on similar principles. The main differences between the different categories will first be explained and thereafter in (more or less) chronological order as they appear in literature will the different CSHs be discussed. Two tables that review and list all the CSHs, their inventor or the researchers that have applied the heuristics and the operation of the heuristics are included (Tables 3.9 and 3.10).

CSHs with *time* and *cost* prioritising

This category includes a range of rules that prioritise jobs with the lowest changeover time or cost. It should be noted that short times do not necessarily mean a cost gain. For example, a really fast changeover i.e. changing tyres on a Formula 1 car takes less than ten seconds and is indeed a fast changeover, but does also require a lot of resources, and may therefore be expensive. However, in the manufacturing literature the general assumption is that short changeover times also cost less. Time and cost have therefore been grouped in this section. The difference between the short time and lowest cost rules and the CSHs that aim to choose jobs with similar or identical set-ups in sequence is that; for instance, a job may have an identical changeover (i.e. using the same tools) to the current job, but it may be a job which requires more tool changes or has a longer changeover time than another job in the queue. The category

of CSHs that prioritises time and costing is therefore different from the similar and identical changeover category.
The *Simset* heuristic (i.e. shortest actual set-up time) is an example of a CSH where the job in the queue with the shortest set-up time is selected (Wilbrecht and Prescott, 1969). Another example is the "*minimise tool changes*" heuristic, which prioritises jobs with the least number of tool changes (Lockett and Muhlemann, 1972).

Group scheduling or *product family heuristics*

This category is based on the assumption that jobs are divided into groups or product families, based on similar characteristics, e.g. jobs with similar or identical changeover times are grouped together. Therefore, to reduce changeover (and inevitable processing times) CSHs in this category aim to schedule jobs within the same group (family) in sequence.

CSHs for group scheduling can be exhaustive or non-exhaustive. An exhaustive heuristic will schedule *all* available jobs from the same product family and will not consider that other jobs may be late because they belong to a different product family and are sequenced late. Whereas a non-extensive rule can be described as a "break" rule, which will schedule a limited number of jobs from one product family until an over-riding criteria is reached and a different product family is selected. It is common that exhaustive CSHs become non-exhaustive CSHs with the assistance of simple priority rules, processing time or due date sensitive rules. For example, the heuristic may be to schedule the same family in sequence until a maximum 5 jobs are scheduled. Thereafter a different family is selected according to a priority rule e.g. the next job in the queue (FCFS) or the job with the earliest due date (EDD).

Details of CSHs approaches

Wilbrecht and Prescott (1969) simulated a job shop to determine the effect of different job priority rules involving set-up times on shop performance. The researchers based their work on experience with an electronics company, testing a total of 7 heuristics and with three involving set-up times. Namely;

- *Simset:* Prioritises jobs with the shortest actual set-up time.
- *Shortest Process:* Prioritises jobs with shortest sum of processing and set-up time.
- *Longest Process:* Prioritises jobs with the longest sum of processing and set-up time.

They investigated ten performance measures on a job shop simulation model with nine machines. Their study showed that overall the Simset rule performed best, although the authors are not sure why exactly this is. The study highlighted that set-up time plays a critical role in the performance of the shop.

Mosier *et al.* (1984) compared three group technology heuristics named AVE (prioritises average priority across all jobs in the queue), WORK (prioritises jobs with longest sum of processing and set-up time) and ECON (compares expected set-up time for jobs in present queue with jobs in the other two queues). Mosier *et al.* (1984) conclude that overall WORK and ECON perform better than AVE.

The repetitive lots (RL) concept was developed by Jacob and Braggs (1988). The new features that RL used were; operations batch sizes which vary by operation, transfer of work within the shop in quantities less than the operation batch size and the use of overlapped operations. The RL procedures first element determines how work is released into the shop. The second element is that release batches are converted into a set of small independent transfer batches, i.e. jobs enter the production system together, but are capable of being processed separately.

The RL procedure ranks jobs in the queue using either FISFS (First In System First Served) or SOT (Shortest Operation Time). Thereafter, jobs are selected for processing;

1. If the queue is empty the next job to arrive starts processing.
2. If the queue is not empty, the queue is checked sequentially for a job of the same type as the job just completed. If there is no job which is the same, the first job in the queue is selected.

The results were compared to running the simulation without the RL concept. Flow times were found to be significantly lower for all combinations or release-batch and transfer-batch size when the RL procedure was applied. The greatest impact of RL on flow time was observed for small release-batch sizes. However, smaller batches increase set-up requirements.

The RL concept has also been applied by Flynn (1987a). In this study the author uses FCFS as the "help rule" when swapping to a different family (job type). Attempting to improve the RL procedure the Truncated Repetitive Lots procedure was developed (Flynn, 1987a). The TRL rule prevents lots from becoming excessively large by allowing no more than K jobs to be combined. This study sets K to five. Computer simulation was used to compare the performance of the RL rules in a job shop, a GT (Group Technology) shop and a hybrid shop (GT + job shop). Three heuristics were tested RL, TRL and FCFS. The sequence-dependent set-up times used by Flynn (1987a) were;

- Between *identical* lots (jobs) there is no set-up time.
- Between *similar* lots (jobs) there is a "production system set-up time" of 0.25 days.
- Between *completely different* lots (jobs) there is a "production system set-up time" of one day.

Although three levels of set-up-times are introduced the RL procedure only sequences jobs according to identical set-up times, no consideration is given to improving the procedure by scheduling similar lots. In Flynn's research RL lead to an improvement over the FCFS heuristic, especially for the GT shop. There was no substantial difference between RL and TRL. This was thought to be because of the relatively high value of K and relatively low utilisation. The investigation of group technology and cellular manufacturing was continued Flynn (1987b). Here two types of shops are investigated; The DED (DEDicated machines) or GT (Group Technology) shop applies the concept of dedicated machines and the CELL or Hybrid shop has both cellular layout and dedicated machines. In the previous study (Flynn, 1987a), the machine utilisation rate averaged 90% in the traditional job shop environment and 60% in the GT and Hybrid shop. The dedication of machines led to much shorter average set-up time, because of similarities of parts produced in sequence. Therefore, in this study the inter arrival rate or jobs were increased for the GT and Hybrid shop to create an utilisation of 90%.

Three research questions were considered for their work;

- Would output capacity increase if utilisation rate was increased from 60% to 90%? To test this only FCFS is applied to both models with an increased arrival rate.
- How is cost on other performance variables affected with increased utilisation?
- What is the effect of RL and TRL on performance when utilisation levels are increased?

Flynn (1987b) concludes that reducing set-up time can increase shop output capacity, even in shops which do not use cellular grouping. Furthermore, when utilisation was increased in order to increase capacity, problems associated with other performance variables can be lessened applying the RL and TRL procedures, where TRL showed the highest increase in performance.

Mahmoodi *et al.* (1990), have tested three CSHs. FCFAM (abbreviation not explained in paper; assumed to mean First Come FAMily) chooses the sub-family queue whose first job in the queue arrived first, whereas, DDFAM (abbreviation not explained in paper; assumed to mean Due Date FAMily) chooses the sub-family queue whose first job has the earliest due date. The third family heuristic, MSFAM (abbreviation not explained in paper; assumed to mean Minimum Set-up FAMily), chooses the sub-family queue that requires the least amount of set-up time at each work centre. Before applying one of the three family heuristics each queue is sequenced according to; FCFS, SPT or T-SPT. In general, the heuristics that utilised the DDFAM and MSFAM together with SPT or T-SPT showed the best performance.

As DDFAM and MSFAM performed well they were applied again (Mahmoodi and Dooley, 1991), using SLFAM (abbreviation not explained in paper; assumed to mean SLack FAMily) and DKFAM (abbreviation not explained in paper; assumed to mean Due date Constant (K) FAMily). The SLFAM rule operateed such as if slack time is larger or equal to zero for *all* sub-families, it keeps processing from the current sub-family. DKFAM is similar to DDFAM, but operates such as; if the due date of the first job in the current sub-family is up to a constant "C" time units longer than the first jobs of the other sub-families it keeps processing this sub-family, otherwise switch to the sub-family whose first job has a more imminent due date. This study showed that exhaustive heuristics performed better than non-exhaustive and in particular, MSFAM performed well.

Mahmoodi *et al.* (1992) applied four family heuristics, FCFCFS (abbreviation not explained in paper; assumed to mean First Come First Come First Served), DDSI (abbreviation not explained in paper; assumed to mean Due Date Shortest Imminent), MSSPT (abbreviation not explained in paper; assumed to mean Minimum Set-up Shortest Processing Time) and ECSI. FCFCFS aim to schedule identical jobs in sequence. DDSI works as the DKFAM rule, but queues are sorted according to a T-SPT (Truncated Shortest Processing Time). The MSSPT rule sequence jobs according to SPT (Shortest Processing Time) and selects the sub-family queue which requires the least amount of set-up time. The results showed that the DDSI heuristics performed best and the MSSPT performed second best.

The CSHs MSSPT, DDSI and ESCI (same as ECSI) were tested again by Ruben *et al.* (1993). This study also included the WORK heuristic (Mosier *et al.*, 1984) and the FCFCFS heuristic (Flynn, 1987a, Mahmoodi *et al.*, 1990 and Mahmoodi *et al.*, 1992). The results revealed that the choice of family rule will depend on the performance measures, which are of interest. For example, MSSPT is the choice if throughput performance is important, while DDSI and FCFCFS perform better according to due dates and ESCI shows the best trade-off between due date and average time in system.

The LPTMM (abbreviation not explained in paper) heuristic is presented by Mahmoodi and Martin (1997). The LPTMM operates such as when a sub-family is completed, the next sub-family is selected subject to a maximum sum of expected processing and set-up time. The LPTMM is tested in conjunction with FCFS and SPT and the other two heuristics tested are FCFAM and MSFAM. Major set-up times are considered sequence-dependent and are incurred when swapping between different sub-families. There are supposedly minor set-up times between jobs within the same sub-family. However, these are incorporated in the processing times. The LPTMM heuristics showed superior performance especially in conjunction with the SPT rule. They concluded that the LPTMM heuristic seek to minimise the number of major set-ups by choosing the sub-family which contains the largest expected work content.

Simons (1992) have developed two family heuristics named TOTAL and SETUP. They are both based on "Vogel's Approximation Method (VAM)", which selects cells in a transportation matrix by examining the potential improvement between the two lowest-valued cells in each row and column. The cell selected is the one that produces the greatest improvement over the next lower cell in its row or column. In the flow shop problem, each cell represents a possible consecutive pair of jobs and each iteration produces the selection of a partial sequence of two jobs. The TOTAL heuristic uses the sum of processing and set-up times on all machines as cell entries and the SETUP heuristic uses the sum of set-up times. Both TOTAL and SETUP show worthy performances.

A study of a job shop that classifies and tests heuristics that either involves set-up time and/or due date information was performed by Kim and Bobrowski (1994). A total of four heuristics are tested, two of those are CSHs;

- *Simset:* prioritises jobs with shortest set-up time (Wilbrecht and Prescott, 1969).
- *JCR:* Scans the queue for an identical job to the one just finished, if not identical it selects the job with the smallest Critical Ratio (CR).

The other two rules tested were CR and SPT.

The two CSHs performed better than the traditional rules and as due date became tighter and set-up time ratio increased the disparity between the CSH and traditional approaches was even more apparent.

Kim and Bobrowski (1997) have extended their previous work, basing it on the previous simulation model Kim and Bobrowski (1994). The 1997 study investigated the impact of set-up time variation on sequencing decisions. The set-up time variation is represented by a normal distribution and reflects the variation in skills of set-up crews and other 'noise' in the system. The authors apply the same four heuristics as in Kim and Bobrowski (1994). However, this time they rename the JCR rule JIS. Results report that set-up time variations have a negative impact on shop performance, but the advantages of set-up conscious sequencing rules over conventional rules still remain.

Arzi and Raviv (1998) have studied a re-entrant production line, with focus on the bottleneck work station of the line. They have applied real data from a semi-conductor plant. This work is particularly interesting as it includes real values of processing times, set-up time and also time between machine failures and time to repair. The number of product and sub-products studied is also realistic, with five products (families) and twelve layers (sub-products). This gives a total of 60 job types. The four heuristics tested are named MMS, MMS/L, MMS/G AND MMS/G/L. The MMS (marginal Set-up time) is defined as the required set-up time divided by the number of waiting jobs (of that type). L means that only jobs that arrive within the look-ahead time window are considered to be selected next. G means that preference is given to a part type that belongs to a group (family), which is <u>not</u> running on any machine. The results show that the group extension rules perform well, whereas the look-ahead principle does not produce any significant improvement. It is interesting to see that Arzi and Raviv (1998) have studied a real problem with product families and sub-product families. However, the scheduling heuristics do not aim to group jobs with similar (same) set-up procedure, but chooses the group with the lowest marginal set-up time. Also, the G extension of the rules is interesting as this means that it gives priority to jobs from different families rather than selecting jobs from the same families in sequence.

A CSH named M-EDD is proposed by Jensen *et al.* (1998). This heuristic operates such as; when a machine requires a major set-up, all jobs in each family are placed in EDD order. Then the machines are scanned for set-up conditions. If none of the families waiting are set-up on other machines, then the family that contains the earliest due date is chosen, but if a family is set-up, they compare the EDD of jobs for a family that is not already set-up with the second half of the queue for jobs in families that are already set-up on one machine. If a family is set-up on two machines, the last third of the jobs in the family are used to make the next "family" decision. This rule has also been tested applying SPT instead of EDD (M-SPT). Jensen *et al.* conclude that the M-EDD and M-SPT family-based scheduling rules show a better performance than traditional rules (EDD and SPT), when set-up times exceeds a certain percentage of the processing time, that is if the set-up times are 15% or higher of the processing times. However, for set-up time < 15% of processing time, the M-EDD and M-SPT rules did not show advantage.

Baker (1999) examined heuristics for scheduling jobs on a single machine with the objective of minimising maximum lateness. Set-up times between different job families are present. Four heuristics were tested and three of those were CHSs;

- EDD: Job with earliest due date is prioritised
- GT: Jobs are sequenced in non-decreasing order of their due dates within each family. Families are then sequenced in non-decreasing order of their family due dates.
- Gap/CS: Start with the jobs in EDD order and place them, one at a time, into the sequence. A job is added to the last batch if its family matches the family of the last batch. If not, then consider adding the job to the latest batch already scheduled for its family, otherwise the job is added to the end of the sequence, initiating a new batch. Whenever a job is placed in some batch other than the last, the batches in the partial schedule are re-sequenced to conform to EDD for batches. CS is an additional procedure for combining and splitting batches. This is because the Gap sequence tends to schedule too many batches.

- GT/SC: Sequences jobs like in GT and in addition a procedure for splitting and combining batches is used. This is because the GT sequence tends to schedule too few batches.

A fifth approach, which is a hybrid between Gap/CS and GT/SC is also tested. The hybrid approach calculates values for both Gap/CS and GT/SC and chooses the better of the two. The CSHs rules perform better with a higher ratio of set-up time to processing time and the best results were obtained by running the hybrid rule.

The changeover sensitive heuristics described in this section are summarised in Table 3.9, with explanation of the operation of each heuristic. The heuristics have been grouped together according to the way they operate. They are grouped according to the main operation of heuristic. However, there could be a slight difference in operation such as longest processing time and set-up time of immediate job or the sum or processing time and set-up time of the whole queue.

Changeover Sensitive Heuristics (CSHs) (Table 3.9, Page 1/2)	
Rule and Study	**Operation of Rule**
Shortest set-up time - **Simset** (Wilbrecht and Prescott, 1969) - **Simset** (Kim and Bobrowski, 1994) - **Simset** (Kim and Bobrowski, 1997) - **MSFAM** (Mahmoodi *et al.*, 1990), (Mahmoodi and Dooley, 1991) and (Ruben *et al.*, 1993)	Simset prioritises jobs with the shortest actual set-up time. MSFAM chooses the sub-family queue that requires the least amount to set-up time at each work centre.
Set-up shortest processing time - **MSSPT** (Mahmoodi *et al.*, 1992)	Sequence jobs according to SPT and then selects the sub-family queue which requires the least amount of set-up time.
Shortest sum of set-up and processing time - **Shortest Process** (Wilbrecht and Prescott, 1969)	Prioritises jobs with the shortest sum of processing and set-up time.
Longest sum of set-up and processing time - **Longest Process** (Wilbrecht and Prescott, 1969) - **WORK** (Mosier *et al.*, 1994) and (Ruben *et al.*, 1993) - **LPTMM** (Mahmoodi and Martin, 1997)	Prioritises jobs with the longest sum of processing and set-up time.
Cells in matrix format - **TOTAL** (Simons, 1992) - **SETUP** (Simons, 1992)	Based on "Vogel's Approximation Method (VAM)", which selects cells in a transportation matrix by examining the potential improvement between the two lowest-valued cells in each row and column. The cell with the greatest improvement over the next lower cell in its row or column is selected. The TOTAL heuristic uses the sum of processing and set-up times on all machines as cell entries and the SETUP heuristic uses the sum of set-up times.
Minimum marginal set-up time - **MMS** (Arzi and Raviv, 1998) - **MMS/L** (Arzi and Raviv, 1998) - **MMS/G** (Arzi and Raviv, 1998) - **MMS/G/L** (Arzi and Raviv, 1998)	The marginal set-up time of a job type is defined as the required set-up time divided by the number of waiting jobs (of that type). L means that only jobs that arrive within the look-ahead time window are considered to be selected next. G means that preference is given to a part type that belongs to a group (family), which is not running on any machine.
Economic tradeoff - **ECON** (Mosier *et al.*, 1994) - **ECSI** (Mahmoodi *et al.*, 1992) and (Ruben *et al.*, 1993)	The queues are scanned to see if it is profitable to change queue. It compares expected set-up requirement of all jobs in the present queue with expected set-up requirement of all jobs in one of the other two queues. ECSI is applied in conjunction with T-SPT.
Average priority - **AVE with SLACK** (Mosier *et al.*, 1994) - **AVE with CR1** (Mosier *et al.*, 1994) - **AVE with SPT** (Mosier *et al.*, 1994) - **AVE with CR2** (Mosier *et al.*, 1994) - **AVE with FCFS** (Mosier *et al.*, 1994)	Finds the average priority across all jobs in the queue at present, select the queue on the basis of this priority. Priority rule is either, SLACK, CR1, SPT, CR2 or FCFS. CR1 is divided by "total processing time" and CR2 is divided by "remaining number of operations".
First job in the queue - **FCFAM** (Mahmoodi *et al.*, 1990) and (Mahmoodi and Dooley, 1991) - **DDFAM** (Mahmoodi *et al.*, 1990) and (Mahmoodi and Dooley, 1991) - **DKFAM** (Mahmoodi and Dooley, 1991) - **DDSI** (same as DDFAM + T-SPT) (Mahmoodi *et al.*, 1992) and (Ruben *et al.*, 1993)	Each of the queues are sorted according to FCFS, SPT or T-SPT. Thereafter, FCFAM chooses the sub-family queue whose first job in the queue arrived first. Whereas, DDFAM chooses the sub-family queue whose first job has the earliest due date. DKFAM is similar to DDFAM, but operates such as; if the due date of the first job in the current sub-family is up to a constant "C" time units longer than the first jobs of the other sub-families, keep processing this sub-family, otherwise switch to the sub-family whose first job has a more imminent due date.
Slack and lowest set-up time - **SLFAM** (Mahmoodi and Dooley, 1991)	If overall slack time is larger or equal to zero for *all* sub-families, keep processing from the current sub-family unless it is empty; in which case the sub-family with the lowest set-up time is prioritised. If any sub-family other than the current has a slack below zero, switch to this sub-family. If two sub-families have the same slack, chose the one with the minimum of slack divided by number of jobs in the sub-family queue.
Identical job (Family) FCFS - **RL/FISFS** (Jacobs and Bragg, 1988) - **RL/FCFS** (Flynn, 1987a), (Flynn, 1987b) - **TRL/FCFS** (Flynn, 1987a), (Flynn, 1987b) - **FCFCFS** (Mahmoodi *et al.*, 1990), (Mahmoodi *et al.*, 1992) and and (Ruben *et al.*, 1993) - **FCFS-FAM** (Wemmerlöv and Vakharia, 1991)	Ranks jobs in the queue using FISFS. Thereafter, select jobs for processing as; 1. If the queue is empty the next job to arrive starts processing. 2. If the queue is not empty, the queue is checked sequentially for a job of the same type as the job just completed. If there is no job which is the same, the first job in the queue is selected.

Changeover Sensitive Heuristics (CSHs) (Table 3.9, Page 2/2)	
Rule and Study	**Operation of Rule**
Identical job (Family) SPT - **RL/SOT** (Jacobs and Bragg, 1988)	Ranks jobs in the queue using SOT. Thereafter, select jobs for processing as; 1. If the queue is empty the next job to arrive starts processing. 2. If the queue is not empty, the queue is checked sequentially for a job of the same type as the job just completed. If there is no job which is the same, the first job in the queue is selected.
Family EDD - **GT** (Baker, 1999)	Sequence jobs in non-decreasing order of their due dates within each family. Families are then sequenced in non-decreasing order of their family due dates.
Family EDD + batch creation - **Gap** (Baker, 1999)	Start with the jobs in EDD order and place them, one at a time, into the sequence. A job is added to the last batch if its family matches the family of the last batch. If not, then consider adding the job to the latest batch already scheduled for its family, otherwise the job is added to the end of the sequence, initiation a new batch. Whenever a job is placed in some batch other than the last, the batches in the partial schedule are re-sequenced to conform to EDD for batches.
Family EDD + batch splitting/combining - **Gap/CS** (Baker, 1999) - **GT/SC** (Baker, 1999) - **Hybrid** (Baker, 1999)	Sequence jobs in non-decreasing order of their due dates within each family. Families are then sequenced in non-decreasing order of their family due dates. Thereafter, batch splitting and/or combining is considered.
Family CR - **JCR** (Kim and Bobrowski, 1994) - **JIS** (Kim and Bobrowski, 1997)	Scans the queue for an identical job to the one just finished, if not identical selects the job with the smallest Critical Ratio (CR)
Multiple machine version of family heuristics - **M-EDD** Jensen *et al.* (1998) - **M-SPT** Jensen *et al.* (1998)	When a machine requires a major set-up, jobs in each family are placed in EDD (or SPT) order. Then the machines are scanned for set-up conditions. If none of the families waiting are set-up on other machines, the family that contains the earliest due date is chosen, but if a family is set-up, they compare the EDD of jobs for a family that is not already set-up with the second half of the queue for jobs in families that are already set-up on one machine. If a family is set-up on two machines, the last third of the jobs in the family are used to make the next "family" decision.

Table 3.9: Changeover Sensitive Heuristics (CSHs).

3.4.4 Review of studies that have investigated changeover sensitive heuristics

Section 3.4.3 has reviewed the operation of different CSHs in general terms. This section review the approaches of CSHs in more detail, such as what type of problem have the CSHs been applied to and what experimental factors and conditions have been tested. Table 3.10 outlines the details, in chronological order, of this and the headings are;

<u>Study</u>

By whom did the study take place, i.e. who were the authors.

<u>CSHs</u>

The CSHs that were tested in each study. Refer to Table 3.9 for operation of CSHs.

<u>Experimental conditions</u>

The experimental conditions used for example, arrival frequency of products, due date setting, processing times and set-up times.

<u>Experimental factors</u>

These include for example shop load (utilisation), set-up time to run time ratio, due date tightness and the heuristics applied.

<u>Performance measures</u>

Examples of performance measures studied are; lateness, average lateness, tardiness, average job tardiness, set-up time (less common), idle time (one example), flow time, makespan, average time in system and number of late jobs.

<u>Shop structures</u>

The machine environment which has been investigated, such as, single, parallel, flow shop or job shop.

<u>Product family characteristics</u>

This category outlines how many product families have been studied and other details such as their routings.

<u>Simulation language</u>

Details of what modelling language approach applied in the study.

<u>Real data</u>

This section answers the questions whether an industrial case study with real data was investigated.

Study	CSH(s) Applied	Experimental Conditions / Major Assumptions	Experimental Factors	Performance Measures	Shop Structure(s)	Family Characteristics	Simulation Language (method)	Case Study Data
Wilbrecht and Prescott (1969)	Simset Shortest Process Longest Process	Random arrival between 5 - 25 per week Random processing times, with mean of 6.8125 (according to user distribution) Uniform (1-4) sequence-dependent set-up times 20% of jobs may be routed out of the shop (failure) No data on due date setting	7 heuristics	Work-in-progress No. of processes in a week No. of jobs sent out in a week No. of late processes in a week Distribution of completion time Queue wait time No. of jobs waiting Utilisation No. of jobs waiting in queue for more than a week Size of jobs waiting in queue	Job shop (9 machines)	Do not consider family grouping	Fortran IV	No
Mosier, *et al.* (1984)	AVE WORK ECON	Poisson arrival Exponential number generator sequence-dependent set-up times Due dates using TWK (7 time tot processing times) Bottlenecked shop	Shop load (utilisation) Set-up to run time ratio	Job lateness Job tardiness Set-up time Idle time Flow time Proportion late jobs	Job shop (4 machines)	The 3 initial machines has 3 sub-family queues Routings from 2 to 4 (no cycling)	Simulation (no more information)	No
Jacob and Bragg (1988)	RL/FISFS RL/SOT	Each items weekly demand randomly generated from uniform distribution (60-140 units) Arrival: Fixed Order Quantity (FOQ) release-batch sizing rule Utilisation = 90% with 200 FOQ (72% run time, 18% set-up time, 10% idle)	Range of Fixed Order Quantity (FOQ)	Flow time Queue time Processing time % Set-up time Tot. set-up time Ave. no. of units per set-up	Job shop (10 machines)	10 job types, requiring completion of an average of 5 operations, random routing pattern	Simulation, software not specified	No
Flynn (1987a)	RL/FCFS TRL/FCFS	Exponential processing times (mean 1 day) Sequence-dependent set-up times - Identical lots = no set-up - Similar lots = .25 day set-up - Completely different lots = one day set-up	3 heuristics 3 shop environments - Job Shop - GT shop - Hybrid of Job shop and GT shop	Ave. set-up time Ave. machine utilisation Ave. production lot size Ave. queue length Ave. WIP inventory Ave. waiting time Longest ave. queue Longest ave. wait Ave. flow time	Job shop (39 machines of 10 functional types) GT shop Hybrid shop	10 job types, each part has its own routing, parts require an average of 19.9 operations each	SLAM discrete event simulation	No

Studies including changeover sensitive heuristics (Table 3.10, Page 1/4)								
Study	**CSH(s) Applied**	**Experimental Conditions / Major Assumptions**	**Experimental Factors**	**Performance Measures**	**Shop Structure(s)**	**Family Characteristics**	**Simulation Language (method)**	**Case Study Data**
Flynn (1987b)	RL/FCFS TRL/FCFS	Exponential processing times (mean 1 day) Sequence-dependent set-up times - Identical lots = no set-up - Similar lots = .25 day set-up - Completely different lots = one day set-up	3 heuristics Shop load (utilisation) 2 Shop environments - The concept of dedicated machines (DED). - Cellular environment with both cellular layout and dedicated machines (CELL).	Ave. set-up time Ave. no. batches combined Ave. queue length Ave. WIP inventory Ave. waiting time Ave. flow time	Job shop (39 machines of 10 functional types) Dedicated machines Cellular layout with dedicated machines	10 job types, each part has its own routing fixed between 17 and 27 operations,	Fortran with SLAM discrete event simulation	No
Mahmoodi, *et al.* (1990)	FCFAM DDFAM MSFAM	Poisson arrival Third-order Erlang processing times Second-order Erlang sequence-dependent major set-up times Due dates using TWK Bottlenecked shop	Shop load (utilisation) Set-up to run time ratio Due date tightness	Ave. time in system Ave. job tardiness Ave. % tardy jobs	Job-shop cell (5 work centres)	Job routing generated at arrival Must go through bottleneck 3 sub-families with three queues at each station 12 parts in each sub-family 12 routings 4-5 op. per part (no cycling)	SIMAN (Fortran sub-routines)	No
Mahmoodi and Dooley (1991)	DDFAM MSFAM SLFAM DKFAM	Poisson arrival Third-order Erlang processing times Second-order Erlang sequence-dependent major set-up times Due dates using TWK Bottlenecked shop	Shop load (utilisation) Set-up to run time ratio Due date tightness	Ave. time in system Ave. tardiness % tardy jobs	Job-shop cell (5 work centres)	3 sub-families with three queues at each station 12 parts in each sub-family 12 routings 4-5 op. per part (no cycling)	SIMAN (Fortran sub-routines)	No

Studies including changeover sensitive heuristics (Table 3.10, Page 2/4)								
Study	**CSH(s) Applied**	**Experimental Conditions / Major Assumptions**	**Experimental Factors**	**Performance Measures**	**Shop Structure(s)**	**Family Characteristics**	**Simulation Language (method)**	**Case Study Data**
Mahmoodi, *et al.* (1992)	FCFCFS DDSI MSSPT ECSI	Normal processing times Normal sequence-dependent major set-up times Minor set-up times inc. in processing times Due dates using TWK	Shop load (utilisation) Set-up to run time ratio Due date tightness Interarrival time distribution	Ave. flowtime Ave. tardiness % tardy jobs	Flow-through cell (5 work centres)	3 sub-families 5 parts in each sub-family Identical routings	SIMAN (Fortran sub-routines)	No
Simons (1992)	TOTAL SETUP	Random distributed processing times (range 1-99) Random distributed set-up times (range 1-99)	No data	Makespan	Flow shop	9 combinations of N jobs (5, 10, 15) and M machines (5, 10, 15)	BASICA on IBM PC	No
Ruben, *et al.* (1993)	MSSPT DDSI ECSI WOSI FCFCFS	Third-order Erlang processing times Second-order Erlang sequence-dependent set-up times Due dates using TWK	Cell load (utilisation) Set-up to run time ratio Inter-arrival distributions Sub-family dominance	Ave. time in system Ave. tardiness % tardy jobs Ave. lateness	Job-shop cell (5 work centres)	3 sub-families with three queues at each station 12 parts in each sub-family 12 routings 3-5 op. per part (no cycling)	SIMAN (Fortran sub-routines)	No
Kim and Bobrowski (1994)	JCR Simset	No. of operations is generated from a geometric distribution (1-15) Exponential processing times (mean 2.5) Set-up time matrix Utilisation approximately 90%	4 heuristics Set-up to run time ratio Due date tightness	Ave. set-up time Ave. no. of set-ups per job Proportion tardy jobs Ave. tardiness Ave. flow time Ave. WIP Ave. finished goods inventory Ave. machine utilisation Ave. tot. cost per day	Job-shop (9 work centres)	Six groups of jobs	SLAM II	No

Studies including changeover sensitive heuristics (Table 3.10, Page 3/4)								
Study	**CSH(s) Applied**	**Experimental Conditions / Major Assumptions**	**Experimental Factors**	**Performance Measures**	**Shop Structure(s)**	**Family Characteristics**	**Simulation Language (method)**	**Case Study Data**
Kim and Bobrowski (1997)	JIS (same as JCR) Simset	Poisson arrivals No. of operations is generated from a geometric distribution (1-15) Exponential processing times (mean 2.5) Set-up time matrix Utilisation approximately 90%	4 heuristics Normal distribution for set-up time variation (5 levels) Due date tightness	Proportion tardy jobs Ave. tardiness per job Ave. flow time per job Ave. WIP per day Ave. finished goods inventory per day Ave. machine utilisation Ave. tot. cost per day	Job-shop (9 work centres)	Six groups of jobs	SLAM II	No
Mahmoodi and Martin (1997)	LPTMM FCFAM MSFAM	Poisson arrivals Second-order Erlang sequence-dependent major set-up times Minor set-up times inc. in processing times Due dates using TWK	Shop load (utilisation) Due date tightness	Ave. time in system Ave. tardiness	Single	3 sub-families	SIMAN (Fortran sub-routines)	No
Arzi and Raviv (1998)	MMS MMS/L MMS/G MMS/G/L	Processing times depend of layer (sub-product) (given in table) Long set-up times between different layers and shorter set-up times between products with the same layer (given in matrix) Include "time between machine failures and time to repair) Bottlenecked shop	4 heuristics	Maximum throughput Minimum total set-up time Minimum average set-up time per performed job Minimum total WIP	Re-entrant flow line 94 work stations)	5 Products (families) Each product has 12 layers (sub-products) totally 60 job types	SIMAN IV (Fortran sub-routines)	Yes
Jensen *et al.* (1998)	M-EDD MSPT	Exponential processing times (mean30.5 time units per operation) Exponentially distributed job arrival times (mean 10 time units) Utilisation 85% to 92% Due date according to TWK	4 heuristics (2 family and 2 traditionally) Machine set-up coordination Major set-up time vary from 0% to 70% in increments of 10%	Mean tardiness Tardiness root mean square Mean flow time Average processing time Queue time Set-up time	8 department closed job shop	10 part families (sub-families) with 6 to 10 job types in each (major set-up between part families0	SLAM II Pritsker	No

Studies including changeover sensitive heuristics (Table 3.10, Page 4/4)								
Study	**CSH(s) Applied**	**Experimental Conditions / Major Assumptions**	**Experimental Factors**	**Performance Measures**	**Shop Structure(s)**	**Family Characteristics**	**Simulation Language (method)**	**Case Study Data**
Baker (1999)	GT Gap/CS GT/SC Hybrid	Uniform (1-99) processing times Set-up times calculated from processing times and due date using set-up factor Due dates from uniform distribution	5 heuristics Set-up to run time ratio Due date tightness	Compared to optimal solutions calculated using branch-and-bound	Single	Not information	No information	No

Table 3.10: Studies including changeover sensitive heuristics.

3.5 DISCUSSION AND SUMMARY

This section concludes, which areas of research into changeovers and scheduling and specifically CSHs that require more attention and where the research reported in this thesis has focused.

One of the major outcomes of the literature study was the realisation that rarely were industrial case studies investigated where real data was incorporated into the simulation models. In fact, only one study was found which utilised were real data in conjunction with changeover sensitive heuristics. Furthermore, the scheduling problems investigated in the literature were often limited, such as investigating a small number of machines and a small number of products, which may not be a realistic account of an actual industrial problem. It was therefore considered of importance in this research to investigate realistic sized scheduling problems and utilise real industrial data to validate the proposed heuristics.

The literature reviewed commonly mentioned that major and minor changeover times exist. Although, when a problem is actually investigated it is common to explicitly only consider major changeover times and assume that the minor changeover times are incorporated in the processing times. For example Mahmoodi and Dooley (1991 and 1992) emphasise that there are minor set-up times between sub-families and major set-up times between families. However, the minor set-up times are not separately studied, as in their research they are incorporated in the processing times. The research described in this thesis has investigated both major and minor changeover times explicitly. Mosier *et al.* (1984) and Mahmoodi *et al.* (1992) argue that group scheduling heuristics are two-stage and consist of three decisions;

(a) *When* a new queue of jobs should be selected.

(b) *Which queue* of the remaining (sub-family) queues to select.

(c) *Which job* to select from the chosen queue.

This definition implies that jobs have already been arranged in sub-family queues when the sequencing process starts. Meaning in front of the first processors there will be e.g. three queues of different sub-families to choose from. Those sub-families all belong to the same product families. This assumption is common in many studies, for example, (Mahmoodi *et al.*, 1990, Mahmoodi and Dooley, 1991, Mahmoodi and

Dooley, 1992, Ruben *et al.*, 1993 and Mahmoodi and Martin, 1997). The dimension missing here is the problem of sorting both product families and sub-product families. Having product families and sub-product families of jobs arriving in the same queue adds another dimension to the sequencing and scheduling decision. A decision needs to be made as to *which product family* to choose and then *which sub-product family* to choose and then *which of the sub-product family jobs* to choose. This would require a *three-stage group scheduling heuristic*, rather than the commonly applied two-stage heuristics. A three-stage heuristic would not be applicable in the research by Mosier *et al.* (1984) or Mahmoodi *et al.* (1992) as they are studying scheduling of one cell assigned to a specific product family with its (often three) sub-families. However, in a large job shop where duplication of processing facilities to be arranged in cells would not be possible, for instance, for reasons such as unfeasible investments or limitation of space for facilities of large physical size, the added dimension of also studying product family sequencing needs to be considered. In this thesis therefore three levels of changeover time are reported such as;

1. Full *changeover time* when changing from one product family to another product family.
2. Partial *changeover time* when changing from one sub-family to another sub-family, within the same product family.
3. No *changeover time* required between jobs within the same sub-families.

In this research the emphasis has been placed on changeover time reduction hence the three levels would be;

1. No *changeover time reduction* when going from one product family to another product family
2. Part *changeover time reduction*, changing from one sub-family to another sub-family.
3. Full *changeover time reduction* when processing jobs within the same sub-family in sequence.

The proposed three-stage heuristics therefore require four decisions;

(a) The decision <u>*when*</u> a new queue of jobs should be selected.
(b) The decision <u>*which*</u> product family to select.
(c) The decision <u>*which*</u> sub-product family to select.
(d) The decision <u>*which*</u> job to select from the sub-product family.

None of the reviewed literature showed studies which investigated the impact of long versus short processing times, such as will CSHs perform differently if the processing times are only 10% of the original processing times? This dimension has been investigated in this research.

Regarding product families and sub-product families, product family dominance has been investigated at as well as including product families with relatively longer processing times and comparing these to product families with shorter processing times, the aim being to determine if there is any difference in performance between these types of products.

The research described in this thesis has also studied a large range of performance measures. A total of 10 measures, including some unusual measures such as percentage of late jobs depending on product families have been investigated.

Furthermore, two levels of changeover time reduction have been studied. At the first level no changeover time takes place and all heuristics including CSHs are tested to determine the performance of CSHs when no changeovers are present. The second level considers changeover, meaning if the case study company could, by means of design changes reduce their changeover times, would they also benefit from different scheduling and sequencing techniques?

CHAPTER 4 SCOPE OF RESEARCH AND OUTLINE OF METHODOLOGY

4.1 INTRODUCTION

The increasing demands for responsiveness and agility in manufacturing make scheduling an important area for improvement. The previous chapters have outlined that much research has been undertaken both in scheduling optimisation and reducing changeover time between production batches or new products. However, the advantages and drawbacks of changeover sensitive heuristics on certain areas of the manufacturing process have not been investigated.

Many of the scheduling problems encountered are typically complex and difficult to handle. For these scheduling problems, heuristics rather than exact algorithms are frequently applied. However, the limitations in current heuristic strategies mean that large sized industrial problems are seldom tackled.

In order to improve changeover performance it is necessary to find more powerful heuristics that can deal with the complex variables of the sort found in the real world, with the emphasis on the relationship between scheduling and changeover issues. The variables include changeovers, sequence-dependent set-up times, group technology and lot-sizing.

The task of investigating current and developing new changeover sensitive heuristics (CSHs) is the central focus of this research.

4.2 RESEARCH AIM AND OBJECTIVES

4.2.1 Overall research aim

The overall aim of the work being presented is to investigate the relationship between scheduling and changeovers and to develop new scheduling heuristics that are intelligent enough to optimise both due dates and changeover requirements.

4.2.2 Research objectives

To meet the overall aim of the research the following specific objectives have been investigated.

- Investigate *existing* scheduling *approaches* and *heuristics* currently applied.
- Analyse the extent of the use of *scheduling systems* and other approaches in industry.
- Examine the effectiveness of *existing* scheduling approaches.
- Ascertain the *interdependence* between *scheduling and sequencing* and *changeovers.*
- Develop *simulation models*, which properly reflect the variables found in real industrial changeover environments.
- Investigate a range of heuristics including;
    - *Simple* dispatching rules.
    - *Semi-* changeover sensitive heuristics.
    - *Existing* changeover sensitive heuristics.
    - *New* changeover sensitive heuristics.
- Investigate the performance of the heuristics under different experimental factors, such as;
    - Different levels of *processing times* (e.g. longer and shorter).
    - Different changeover times, such as *major*, *minor* and *none.*
    - Different levels of *changeover time reduction.*
    - Increased batch sizes (increased *utilisation*).
    - Studying a range of different *performance measures.*

4.3 RESEARCH METHODOLOGIES

The research outlined in this thesis has involved the use of several methods and approached applied at different stages of the research process. Initially a questionnaire study and interviews were used to establish industrial practise and to collate case study details. The in-depth case study involved detailed data collection that was modelled in discrete event simulation software. The methodology is based on a set of case study variations. In order to create generic data sets for a job shop environment, the case studies were extended to incorporate a range of parameters, such as several levels of processing times and job grouping strategies.

4.3.1 The survey strategy and questionnaire method

Surveys are wide and inclusive in their coverage, they are conducted at a specific point in time and they are described as empirical research in the sense that 'to survey' carries with it the meaning 'to look' (Denscombe, 1998). They involve the idea of getting out of the chair, going out of the office and purposefully seeking the necessary information 'out there'. The survey strategy suited this research as one of the research objectives was to establish current industrial practice. The literature review of the scheduling and sequencing areas had showed richness in theory, but little applied research was found, as well as limited documentation about common industry practice. Therefore, to gain an understanding about what is happening 'out there' a questionnaire survey was conducted among a cross-section of UK businesses. The questionnaire survey was followed by semi-structured interviews of a smaller number of participants, in order to choose an appropriate case study company.

It is appropriate to use a questionnaire for research when there are a large number of respondents in many locations (Denscombe, 1998). This was true for the research described in this report, where the intent was to cover a larger cross-section of companies located all over the UK. To achieve this and reach as many respondents as possible it was decided to use postal questionnaires and when feasible questionnaires were e-mailed. As recommended by Denscome (1998) "self-completion" questionnaires were used and sent out through the post. This generally involves a large-scale mailing covering a wide geographical area. Other advantages considered when choosing to carrying out a questionnaire survey were that questionnaires can supply a considerable amount or data for relatively low cost and are easier to arrange to get an overview of the area studied before conducting interviews. Also, questionnaires supply standardised answers, because respondents are posed with exactly the same questions and when there is no face-to-face contact between the researcher and the responded, which could affect the answer to the questions.

The questionnaire was designed to include both 'open' and 'closed' questions. Open questions allow the respondent to express his or her view in their own words, whereas closed questions only allow answers which fit into categories and are therefore more structured. The closed questions can be analysed in a quantitative manner. However, both types of questions were needed to establish knowledge of the area being studied. The first questions on the questionnaire were designed to develop a general understanding of the production scheduling area and what may increase the complexity of this area. Questions specifically directed to collect data about the scheduling practices and how the respondents felt about these practices were then asked. Questionnaires are often applied when seeking factual information (background and biographical information, knowledge and behavioural information) and will also include measures of attitudes, values, opinions or beliefs (Punch, 1998).

When analysing the questionnaire data the statistical software SPSS (Statistical Package for the Social Sciences) (SPSS, 2006) and Microsoft Excel were used.

4.3.2 The interview method

Pre-case study interviews were applied for the next step of the research. The pre-case study interviews were a continuation of the questionnaire method where data is studied in more detail. Also, the pre-case study interviews served the purpose of creating a link between the questionnaire method, rich in quantitative data, and the case study method, rich in qualitative data. It is appropriate to use interviews as a follow-up to a questionnaire (Denscombe, 1998), especially, when the questionnaire study has thrown up some interesting lines of enquire, that the researcher can use interviews to pursue in greater detail and depth. The wish to collect more in-depth and detailed data when deciding on a case study was another reason to use pre-case study interviews. The pre-case study interviews were semi-structured and therefore involved collection of both quantitative and qualitative data. The choice of semi-structured interviewing involves the collection of, to some extent quantitative data, because of the questions structured into categories. However, the interviews were very much open for discussion and therefore created qualitative data. The semi-structured interviews required that the interviewer is prepared to be flexible in terms of the order in which the topics are considered, and, perhaps more significantly, to let the interviewee develop ideas and speak more widely on the issues raised by the researcher. The pre-case study interviews were one-to-one and face-to-face interviews. It was considered an advantage to meet the interviewee in person and when applicable also visit the production facilities. The interviews were taped using a dictaphone. The interviews were concluded and summarised in written format and the interviewee was asked to check if the information collected has been understood correctly so to avoid misunderstandings. In other words the results were validated.

4.3.3 The case study strategy

In general, case studies are the preferred strategy when "how" or "why" questions are being posed, when the investigator has little control over events, and when the focus is on a contemporary phenomenon within real-life context (Yin, 2003). These arguments support the decision of applying the case study strategy to the main part of the research. The next step of the research was to investigate current and develop new changeover sensitive heuristics and test those on a real industrial scheduling problem. The strength of the case study approach is that it allows for the use of a variety of methods depending on the circumstances and the specific needs of the situation (Denscombe, 1998 and Gummesson, 1991). They report that a thorough analysis of a particular process will require the use of the researchers' personal observations that result from their presence, participation, or even intervention in the actual process to be examined. Throughout the case study strategy, questionnaires, in-depth face-to-face and telephone interviews, observations and the collation and study of company specific documents took place. Data collected were analysed in MS Excel, and then incorporated into the simulation models. A body of case studies have been undertaken. These are based on extensive data collection at the key collaborating company.

4.3.4 The discrete event simulation approach (Witness (Lanner, 2006))

In the initial stages of the research, industrial information was gathered using postal questionnaires, structured interviews and observations. The findings from the initial stages were used to identify companies for future investigation/research activities. Once the collaborating company had been identified the researcher visited this company on many occasions to gain an understanding of their process as a whole and enable data gathering of their activities. The data was adapted to a format that could be entered into the discrete event simulation software, Witness 2003 Release 2 (Lanner, 2006). This simulation software was selected as it is a tool which is well established and commonly used in industry. Discrete event simulations can model manufacturing systems as they develop over time, with variables changing instantaneously at separate points in time. Witness is a visual system that has an animated graphic display showing elements such as products moving between machines. The visual interface offers the advantage of users being able to observe information such as buffer queues, bottlenecks and job status. Jobs can for instance be modelled in different colours which can be used to represent different stages in the simulation. This can be very useful for validation and verification purposes, especially when verifying that the scheduling rules operate as expected. Witness uses an interactive modelling approach which can assist during model building and verification as the models can be built step-by-step and runs can be executed at each step. During simulation runs the model can be interrupted, changes can be made and the run can continue (Robinson, 2004). Applying this type of simulation to scheduling can be very useful, because it does not only determine the output of different scheduling approaches, but additionally it allows the user to study the whole process of the simulated system, assisting in its understanding. Witness has proved to be a flexible software as it has many inbuilt default functions and icons as well as having the capability for the user to write their own programming code within the Witness interface to replicate their particular system accurately. Within this research the programming function was used for the modelling of different scheduling rules. Several models were built to test different scheduling scenarios. The details of the simulation models are described in Chapter 7.

4.3.5 Summary of research methodologies

The flow chart in Figure 4.1 displays an overview of the research methodologies. It outlines the different research activities, describing parallel activities throughout the course of the research.

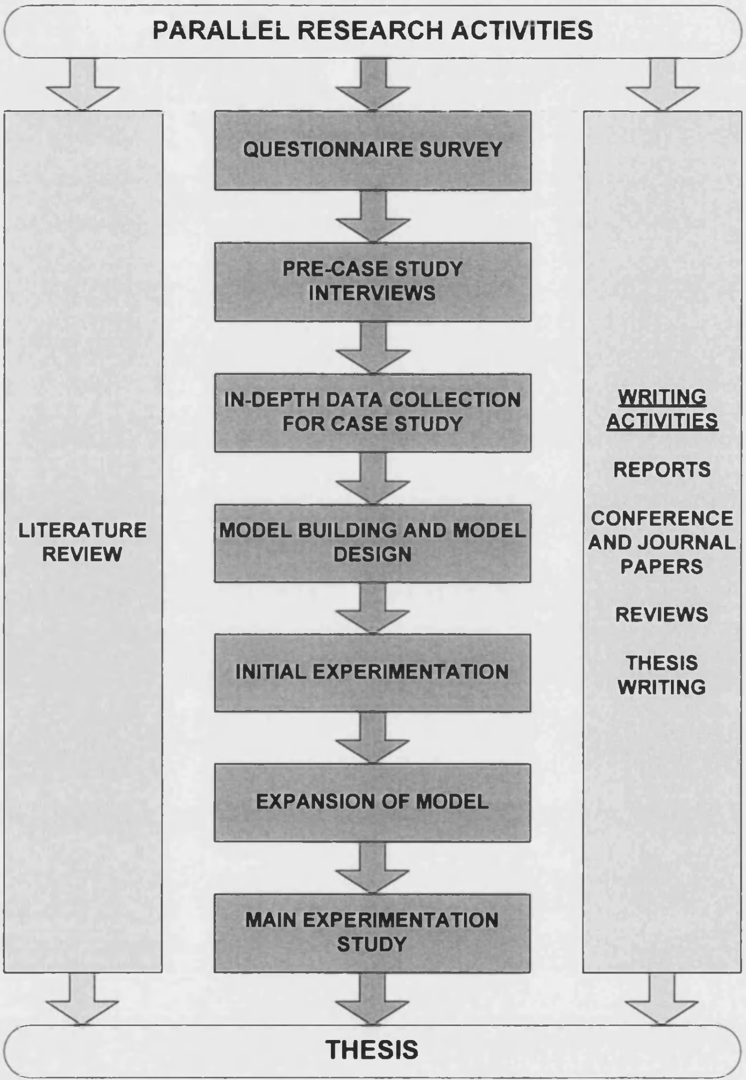


Figure 4.1: Methodology flowchart.

CHAPTER 5 QUESTIONNAIRE SURVEY AND PRE-CASE STUDY INTERVIEWS

5.1 INTRODUCTION

The literature review of scheduling and sequencing highlighted that few realistic sized scheduling problems were tackled. Furthermore, there were few accounts on what scheduling approaches and software being applied by industry. In order to investigate this, a questionnaire survey was sent out to a cross-section of UK businesses. Thereafter, pre-case study interviews took place involving a smaller number of companies.

5.2 QUESTIONNAIRE SURVEY

5.2.1 Aims and objectives of questionnaire survey

The overall objectives of the survey was to determine the scheduling requirement of industry and to investigate the type of scheduling systems and heuristics that are currently used, the extent of their use, and their effectiveness.

5.2.2 Questionnaire research questions

The research questions for the questionnaire design arose during the literature review where few examples of realistic sized scheduling problems relevant to industry were found. Therefore, the survey was used to find out actual production scheduling practises in industry and whether scheduling systems and heuristics were being used, and if so the extent of their use, and their effectiveness.

The first set of questions in the survey established the type of business the respondents were in. This was in order to determine whether any common characteristics exist regarding production scheduling and whether the type of business could be related to the level of complexity of the different production procedures. It was also a natural way of grouping them for the data analysis. The next set of questions focused on the level of complexity. Questions were asked about whether batch or continuous production was used, values for output or volume of products, variety of products and the volume of the main product, as well as the level of changeovers. The survey also examined production scheduling issues and how they were dealt with at each company. In relation to this, companies were asked to give a judgement on the level of satisfaction of their applied scheduling approach and why this approach was used. The use of scheduling software and tools, or whether they had considered using such tools was also investigated. Finally, companies were asked if they were interested in further participation in the research. This question was aimed at finding companies that would be interested in further collaboration and participate in the interview process.

The covering letter and questionnaire template that was sent out is included in Appendix A (please refer end of thesis and to attached CD-ROM).

One change was made to the questionnaire design during the course of the study. In the second template one question was added, whether the company was satisfied with their current scheduling approach. The first 165 questionnaires were sent out without this addition (Batch 1). However, the next 227 questionnaires (Batch 2) did incorporate this question. The reason for this addition was that the first batch showed that many businesses used manual scheduling techniques and it was of interest to find out if they were actually satisfied with this.

5.2.3 Questionnaire coverage

Table 5.1 shows the coverage of the questionnaire, the samples and the number of questionnaires sent out. Many of the companies to which questionnaires were sent were found through either "The British Engineering Manufacturers' Association" (BEMA) or in the Applegate register (Applegate Directory, 2003a, 2003b). The Applegate register is an online register of UK companies. Table 5.1 highlights which register was used. The letters before Applegate e.g. A-F and G-J indicate that companies were selected in alphabetic order among those letters.

Batch	Number of questionnaires of each type (samples)	Number of questionnaires in each batch
Batch 1	- 10 Pilot questionnaires (name of specific person known) - 70 BEMA questionnaires - 3 Questionnaires (name of company supplied by one company from the BEMA selection) - 20 Chemical A-F Applegate - 20 Electronic A-F Applegate - 20 Engineering A-F Applegate - 20 Plastic & Rubber A-F Applegate - 2 E-mailed questionnaires	165 Questionnaires
Batch 2	- 21 Electronic Systems - 20 Chemical G-J Applegate - 20 Electronic G-J Applegate - 20 Engineering G-J Applegate - 20 Plastic Rubber G-J Applegate - 20 Chemical K-N Applegate - 20 Electronic K-N Applegate - 20 Engineering K-N Applegate - 20 Plastic & Rubber K-N Applegate - 42 Food K-N Applegate - 4 E-mailed questionnaires	227 Questionnaires
Total number of questionnaires		392 Questionnaires

Table 5.1: Sample and number of questionnaires sent.

The questionnaires were sent in two batches. The two batches were compared and the differences and similarities analysed when the number of responding questionnaires more than doubled. The first ten questionnaires sent out were to companies that the Mechanical Engineering Department at the University of Bath had worked with in the past. The names of appropriate persons at each of these ten companies were known and the letters were sent directly to these contacts. The aim was to use the first ten questionnaires as a pilot study. This sample was selected because it was easy accessibly, names of specific people at respective company were known, and the response rate was expected to be high. The next sample came from the BEMA Handbook (April 2002 and Feb. 2003). BEMA based in Bristol produces a monthly handbook that contains a directory of their members. 70 companies were selected from the BEMA directory. Every effort was made to select the companies in a statistically sound manner. The method used was that every fourth company on the alphabetic list was selected. Although, when “the fourth” company was not a manufacturing businesses the previous company, that is the company just above it in the list, was picked. If this company was also not a manufacturing business, then the next company, the company just below in the list, was selected. It was decided to use the BEMA directory because it was accessible, contained many local companies of which many were manufacturing businesses. Company details for another three companies were also supplied by one of the responding companies from the BEMA sample. The company that received the questionnaire did not consider their company appropriate to participate, but instead supplied details of three of their customers. The Internet based company directory Applegate (Jan. – Feb. 2003a and March - April 2003b) was used for the majority of the samples. The Applegate directory encompassed company details of industry, technology and manufacturing in the UK and Ireland, over 47,000 companies. Using the computer mouse and clicking randomly on the list of companies, selected companies on a reasonably random basis. However, only manufacturing businesses were required for the survey so therefore the random approach was constrained. When a selected company was not a manufacturer another company was randomly picked to replace it. Food manufacturing companies were not included in the first batch among the sample developed from the Applegate directory; this was because for Batch 1 there was not an Applegate food directory available. For Batch 2 a food industry section was added to the directory and companies from this list were included (Table 5.1). The Applegate directory was chosen for the main survey samples because of its accessibility, the amount of companies included in the directory and the fact that it was useful to be able to select companies from different types of businesses so ensuring that the questionnaires reached a large cross-section of industry. Furthermore, a contact in the food industry supplied names of six companies, names of appropriate persons and their e-mail addresses. Because e-mail addresses were known for these six companies the questionnaire was sent out by e-mail instead of by post. These are the samples called e-mailed questionnaires. When the findings and results from the first batch were analysed, it was realised that none of the electronic businesses included in the first batch had responded. Therefore, to obtain more responses from this sector in Batch 2, the catalogue "Electronics Systems Design in the UK (2001)", was used and another 21 electronic businesses were selected.

5.2.4 Questionnaire data collection and analysis

The majority of questionnaires were sent by post, and a few were e-mailed when such details were known. If the name of an appropriate person to fill out the questionnaire was know for a specific company, the letter was addressed to this person. However, for most questionnaires, this information was not available. In those cases letters were addressed to the "Operation Director" at each company. The choice of postal questionnaires was made for two reasons; it was thought that postal questionnaires would give a higher response rate since they were considered to appear more serious than a blanket e-mail approach. It was also considered more straightforward to find the address of a company and direct the letter to a certain job position rather than using a general e-mail address. Included in each envelope with the questionnaire were a covering letter and an addressed envelope for the questionnaire to be returned in.

A total number of 392 questionnaires were sent out. 68 of these were returned and are included in the survey. This gives a response rate of 17.3%. For this type of survey, the response rate received, of 17.3%, is considered high (Malhotra and Birks, 2000). This can to some extent be explained by the fact that names of certain persons at some of the companies were known and for questionnaires that were e-mailed, they were directed to a particular person. Another issue that probably had an impact on the response rate is that effort was made to carefully pick companies that had manufacturing facilities, so that the survey would be relevant to them. The simple design of the questionnaire and covering letter may also have increased the number of respondents. Furthermore, it is worth noting that there were also positive responses among the questionnaires that were sent to companies not appropriate for the research. For instance, one company supplied addresses of some of their customers that were more appropriate to the survey. Some of the selected companies responded explaining and giving reasons why they could not participate and this was appreciated by the researcher. The response rate including these responses was 19.9%. Perhaps the high response rate could also be an indication that scheduling is important and an area of interest to many companies, though this is of course just a theory.

Figure 5.1 and Table 5.2, show the number of respondent businesses distributed over five categories.

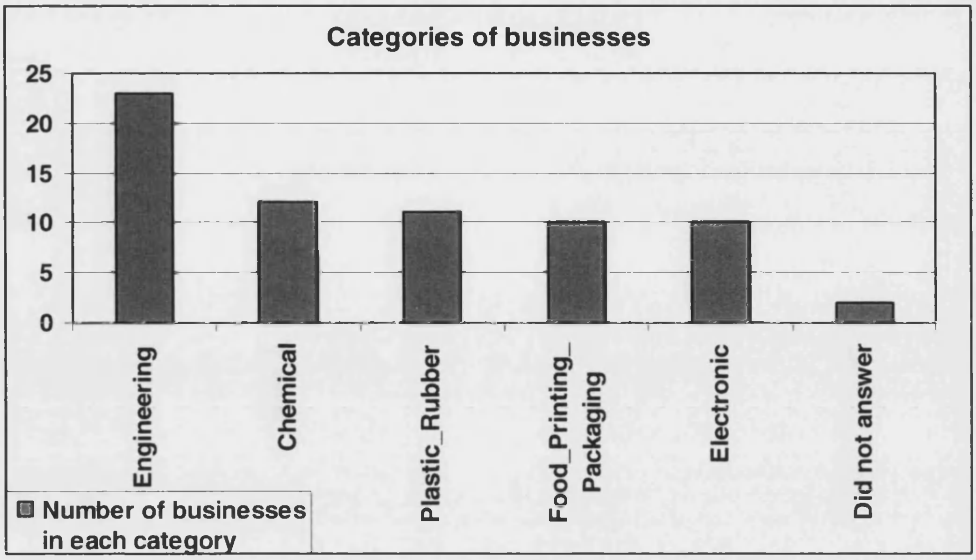


Figure 5.1: The number of respondent businesses distributed over five categories.

Business Category	Number of Businesses
Engineering	23
Chemical	12
Plastic_Rubber	11
Food_Printing_Packaging	10
Electronic	10
Did not answer	2

Table 5.2: Key to graph in Figure 5.1.

The survey focused on a cross-section of businesses including companies of different sizes. The responding companies were categorised and grouped according to their type of business. The category named ‘Engineering’ is broad and includes among others aerospace, automotive and precision engineering companies. There is one category for chemical and one for electronic companies, one category includes both plastic and rubber businesses. Food manufacturers, printing and packaging companies have been grouped together, as it was considered that those types of businesses might have common characteristics regarding scheduling practices. Two companies did not reveal in what area of business they were working.

The companies that were sent questionnaires had the choice of not participating, thus presumably the companies that responded did not have any reason to purposely give false data and therefore the quality of the data can be assumed to be high. However, the quality of the data also depends on the knowledge of the particular person that answered the questionnaire and this could have reduced the data quality.

The statistical software SPSS and Microsoft Excel have been used for analysing the collected data. The data collected was documented in SPSS, from were tables of frequencies were extracted. The cross tabulation function in SPSS was used to study for instance, how many of the companies that said they used manual scheduling had looked at scheduling software solution. The graphs included in this chapter have been exported from Microsoft Excel.

5.2.5 Result and findings from the questionnaire survey

The main findings of the questionnaire survey are displayed in Figure 5.2 to Figure 5.4. The three figures each include a smaller graph, named Figure (b). These smaller graphs show the respective result for that section after the responses of Batch 1 had been analysed. Batch 1 included 31 responses and Batch 2 included 37 responses. When percentages are given in the text below there is a figure in brackets after each percentage; this shows the result from Batch 1. The comparison between the results from the first batch and the second batch demonstrate that the survey included a reasonable number of respondents and is a realistic account of the scheduling practises among U.K. industries.

One of the main results concluded by the survey was that 58% (62%) of the respondent companies said that they were using *manual scheduling approaches*, such as spreadsheets (Figure 5.2 (a) and 2 (b)). Furthermore, in total 35% (32%) of the respondent were using some type of scheduling system or tool (scheduling package, scheduling module included in an ERP or MRP system or scheduling software developed especially for a specific company need).

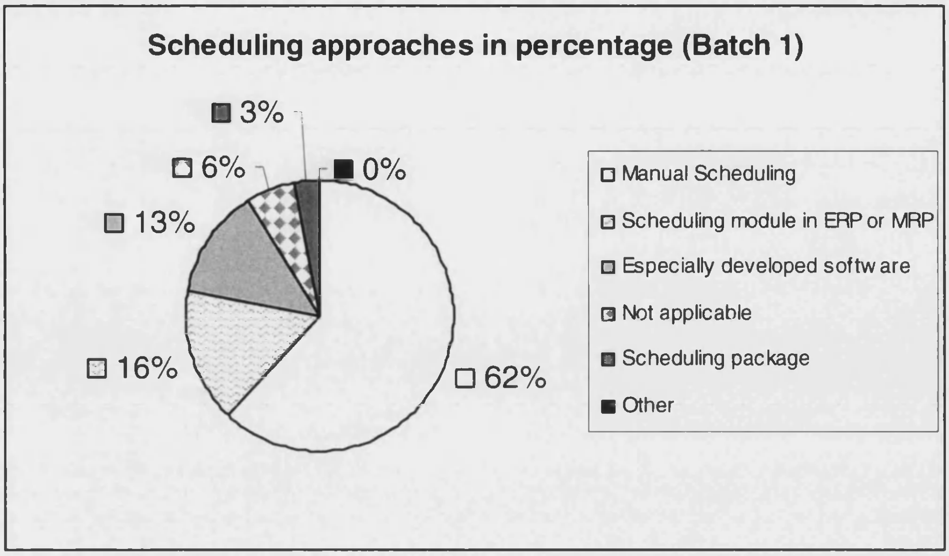


Figure 5.2a: Scheduling approaches applied – Result Batch 1.

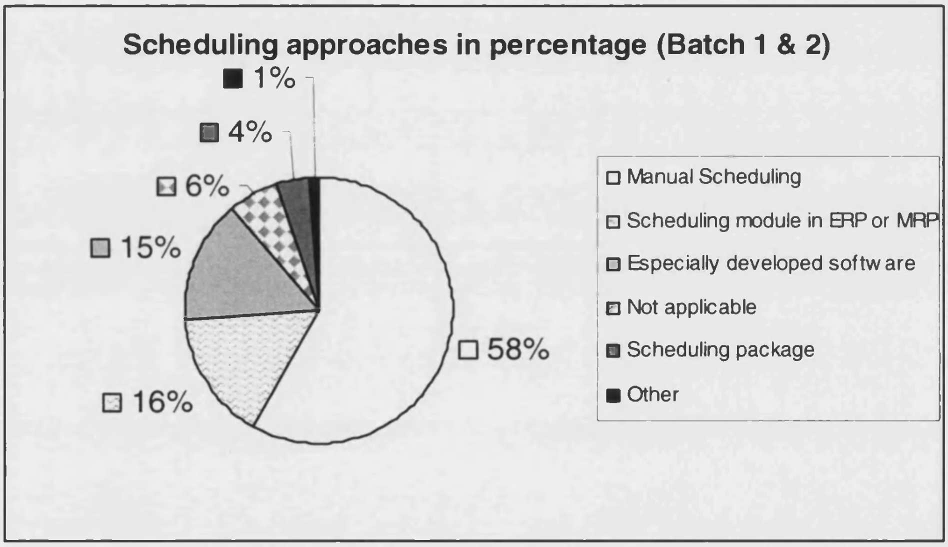


Figure 5.2b: Scheduling approaches applied – Result Batch 1 & 2.

The reasons given as to why companies had chosen a manual scheduling approach included; scheduling software is expensive; their operations are too complex; it is a legacy and something the company has grown into. Some companies answered that they preferred the manual approach because it is a simple and easy method to use. Whereas others actually considered the manual approach flexible and sufficient for their needs.

38% (42%) of the companies that applied a manual scheduling approach had looked at scheduling software solutions. This illustrates a level of interest other than the manual in the area of production scheduling and the need for different solutions. However, it should also be noted that some companies found that the manual scheduling approach was sufficient and more appropriate for their needs. Respondents were asked whether they were interested in discussing their scheduling approach further and 41% (48%) of the companies showed their interest and were willing to participate in the extension of the research project.

32% (36%) of the companies recognised that there was a need for scheduling software specifically developed for their needs, while 32% (29%) of the respondents do not believe that this approach is helpful. Another 31% (32%) are unsure if this would benefit them and 5% (3%) did not answer (Figure 5.3 (a) and (b)). It is difficult to draw conclusions from this sample. The preferred approach to scheduling will most likely depend on the type of business and a particular company's scheduling requirements.

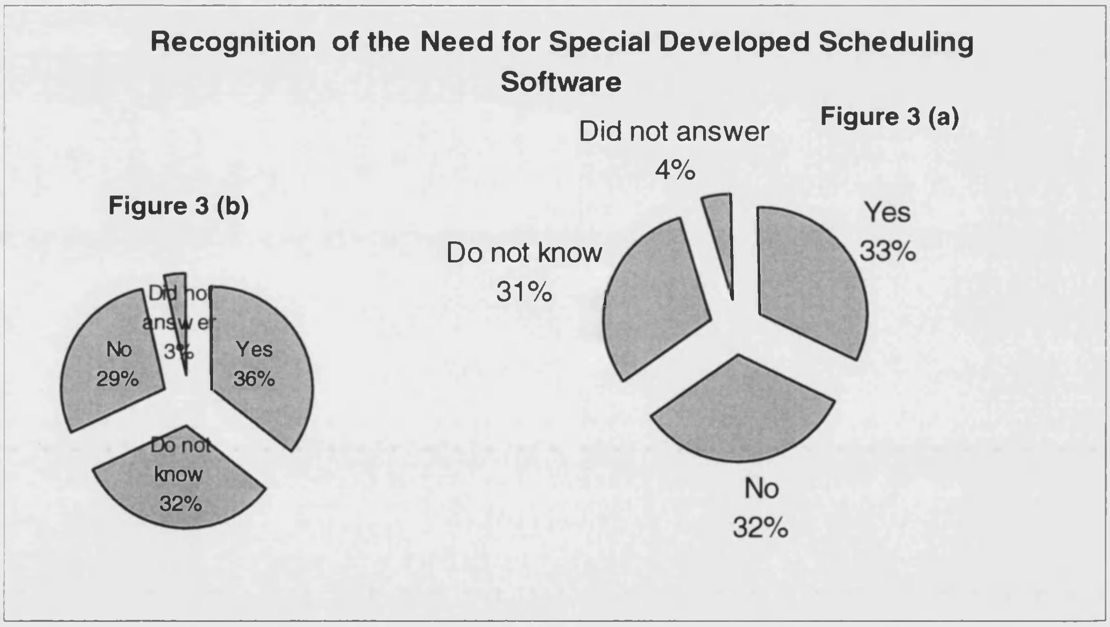


Figure 5.3 (a) and (b): Recognition of the need for special developed scheduling software.

The survey also sought to establish whether scheduling rules were commonly applied or not (Figure 5.4 (a) and (b)).

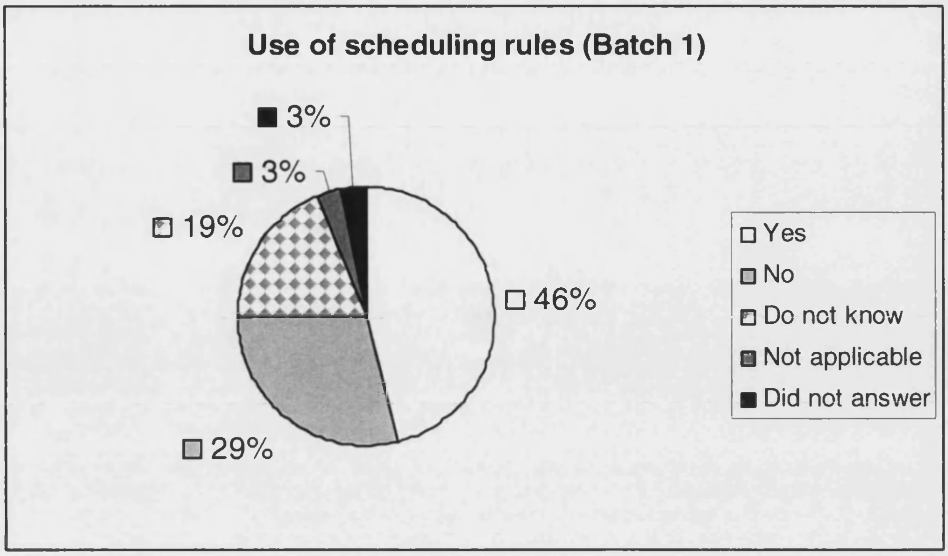


Figure 5.4a: Use of scheduling rules – Result Batch 1.

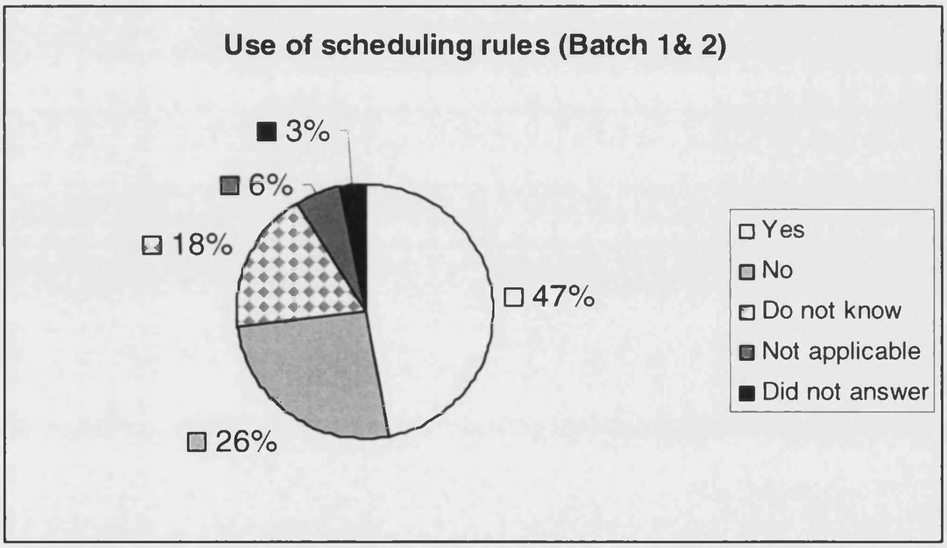


Figure 5.4b: Use of scheduling rules – Result Batch 1 & 2.

A number of different scheduling software and tools were identified by companies during the investigation. They are either used by companies or are scheduling solutions being investigated and considered by the companies for future use.

5.2.6 Conclusion and discussion of the questionnaire survey

The results from the questionnaire survey are indicative and not the main focus of this research. The survey focused on a cross-section of businesses including companies of different sizes. The comparison between the findings from the first batch and the findings from the second batch, where the number of respondents more than doubled, shows that the survey include a reasonably number of respondents and is a realistic description of the scheduling practises among U.K. industries. The result from the questionnaire survey are published in, Eriksson *et al.* (2003). The questionnaire results showed that, although numerous scheduling tools exist, scheduling manually is by far the most commonly applied in industry. This suggests a lack of understanding in the area of production scheduling and that perhaps different aspects of the problems may need consideration and different approaches needed to solve the problem. The reasons companies gave for sticking with the manual scheduling approach emphasised that there is a need for affordable scheduling software with user-friendly interface, user-defined features that can be applied to a company's specific needs and offers re-scheduling abilities that are can be performed within a reasonable time.

5.3 PRE-CASE STUDY INTERVIEWS

After the questionnaire survey was completed and the results and findings analysed it was realised that more detailed information about different companies scheduling practices would be useful to assist in identifying appropriate case studies. Interviews were therefore conducted with some of the companies that participated in the questionnaire survey. When using the interview approach the aim was to explore the topic in greater detail and depth than the questionnaire survey could give.

The companies interviewed were selected from those that responded to the questionnaire survey and showed interest in further participation. The type of interview chosen was 'semi-structured one-to-one face-to-face interviews'. This meant that the interviewer had a clear list of the research categories and questions to be addressed. However, the questions were aimed to enable open discussion and the interviewer was flexible in terms of the order of the topics. The interviewee could also develop ideas and speak more widely on the issues raised by the researcher. Interviews carried out on the company sites enabled tours of the actual production facilities. Interviews were documented using tape recorder and as compliment written notes were made.

5.3.1 Aims and objectives of pre-case study interviews

The aims and objectives of the pre-case study interviews were to understand and map details of the scheduling requirements of the companies interviewed. Information gathering regarding scheduling techniques and identification of failures and successes that companies had had with scheduling and sequencing were also performed. The pre-case study interviews were also a means of determining a suitable case study company for in-depth collaboration.

5.3.2 Pre-case study interviews research categories

The scheduling topics or categories investigated by the interviews were developed from queries arising when studying the scheduling literature and from the outcome of the questionnaire survey. The interview research questions were structured into seven categories.

Category 1: Introductory questions

The introductory questions were of a general nature, such as the first question asking the interviewee what his or her position and responsibility is at the company. The introductory questions aim to establish some basic information about the company, e.g. the number of employees. The questions also serve the purpose of offering the interviewee the chance to settle down and relax, since these are questions that the interviewee presumably will feel comfortable to answer.

Category 2: Description of production processes and operational procedures and the complexity of manufacturing processes

The questions in this category aimed to get an understanding of the manufacturing processes as a whole. This provided data to compare differences and similarities between the production companies.

Category 3: Manual production scheduling

Category 3 considers and discusses manual scheduling and its advantages and disadvantages. When and why is it used? When this could be the preferred scheduling approach and what tools and techniques are used to assist manual scheduling?

Category 4: The application of scheduling software packages or other computerised scheduling tools

This section investigates the use of scheduling specific software. What are the advantages and disadvantages of this approach? When and why is it used? When could this be the preferred scheduling approach? Are other tools and techniques used to assist the scheduling software? Which software is chosen and what does it offer? Is manual scheduling still partly necessary? How was scheduling performed before the software was taken into use and what can be said to have been improved or become worse? Have they noted anything like for instance better product quality? If the company is not using scheduling software, would they consider using one?

Category 5: Identification of scheduling problems and implications

Production scheduling can be a very complex task that involves a range of considerations and constraints. It was of interest to find out what the different companies consider to be their main problems, impacts and disturbances to their schedule. Are there common characteristics among the companies or are those implications specific for each company or type of business?

Category 6: Successful scheduling solutions and improvements

As stated previously scheduling and sequencing can be a difficult task. However, there may also be success stories, clever solutions and useful improvements taking place. The emphasis can often be on the problems and difficulties, while the actual accomplishments are forgotten. Therefore, the next aspect was to investigate what successes the companies have had within scheduling. The aim of this was to investigate whether these advantages could be applied within different types of businesses.

Category 7: Scheduling organisation

This category is aimed at assessing the emphasis of scheduling within the company and how scheduling tasks are organised. What attention is scheduling receiving? Is the importance of scheduling emphasised? How many are involved in production scheduling? What is their knowledge of the process and is experience a requirement? What improvement activities are taking place regarding scheduling, such as regular meetings and training? Are scheduling heuristics (rules) applied and if so what are these? Do informal scheduling rules exist, for instance, the most important customers order is processed first? Is the company meeting the set delivery dates?

The interview questionnaire template is available in Appendix B (please refer end of thesis and to attached CD-ROM). The questions are intended to open up discussions of the topics as well as providing the core data required for the analysis.

5.3.3 Pre-case study interviews coverage

The interviews aimed to collect more extensive and more intensive data than the questionnaire survey. In order to be able to draw conclusions from the interview sample such as similarities and differences between different types of manufacturing companies regarding production scheduling and its related problems, the mix of manufacturing companies and different scheduling applications, e.g. manual scheduling or using scheduling software, were considered essential. In forming the group of companies to interview coverage of a range of different manufacturing processes rather than focusing on one specific sector was used.

When studying the questionnaires to find suitable companies for participation in the interviews, the respective companies' enthusiasm for further participation also had to be taken into consideration. On the questionnaire companies were asked if they would be interested in further participation in the research and so the sample for the interviews was limited to those that had been positive in partaking. If companies had said no or given a reason why they could not participate, this of course had to be respected.

The final number of pre-case study interviews was settled on five businesses.

5.3.4 Pre-case study interview data collection and analysis

The interviews were documented using a dictaphone and as a compliment to the tape recording, written notes were taken. In this thesis the interviews are summarised from the information on the tapes and from the notes taken. For a full coverage of the interviews, please refer to the Report Register at the University of Bath, Mechanical Engineering department, where the tapes are stored (Eriksson, 2006, Report No. 07/06).

5.3.5 Pre-case study interview procedures

Interviews took place face-to-face and all interviews except one took place at the actually company site. After introductions and a possible tour of the manufacturing area, the interviewee and the researcher sat down in a relaxing and if possible quite environment.

Before the actual interview began the interviewee was informed or asked about:

- That the interview is confidential;

- Asked if the interviewee would like a brief explanation about the research;
- The interviewee may be asked to (if he/she likes to) read what has been concluded from the interview to avoid misunderstandings and allow feedback.
- The structure of the interview and that the questions are divided into seven categories;
- Asked if the interviewee did not mind the use of tape recording. If there was no problem with this the tape recorder was set up and tested;
- Asked if he/she has any questions before the interview commenced.

Thereafter, the postal questionnaire that the interviewee or someone else at the company filled out in a response to the questionnaire survey was discussed. This was incorporated to collect more detailed data and make sure the researcher had interpreted the answers correctly. The interview then moved on to the interview template with its seven categories. Given that the interviews were semi-structured and open for discussions, the categories may not necessarily be discussed in the order in which they were set up, but the intention was to cover all categories.

5.3.6 Result and findings from pre-case study interviews

Five companies were interviewed and in order not to disclosure details on company information they are here named A, B, C, D and E. The interviews and findings from the five companies are summarised in this section. However, note that the description of Company D's productions process is more detailed than the others. This is because the interview with Company D involved a whole day visit with a thorough tour of the shop floor, and meeting more than one interviewee, whereas the other interviews lasted an hour with one interviewee.

Company A

Company A is a manufacturer of oil tank gauges and delivery systems for diesel. They are also offered sub-contracting jobs. Their production is batch based. Depending on the product the weekly output ranges from less than ten up to several thousand. The company manufacturers up to 100 different product types, fifty of these being sub-contract. The weekly volume of the main variant is between 50 to 500 parts per week.

The shop consists of an assembly area and a machine shop. In the assembly area changeovers takes place less than five times per week, whereas in the machine shop there are over 20 changeovers per week. Scheduling is performed daily using a manual approach. They explain this by saying that they currently use a manufacturing software system called Micross. This software has a scheduling package, but they decided not to use this functionally as they found their manual system easier to operate in conjunction with the rest of the Micross software. Their manual system is board based, using physical boards located on the office wall. The boards have a bar system, in Gantt format, where bars can be moved and manipulated until a feasible schedule is formed. Furthermore, they state that they do not apply scheduling rules or heuristics. Company A was happy with their scheduling approach and did not consider that scheduling software especially designed for their company's need would be helpful.

Company B

Company B manufactures and directly sells conservatory blinds. The production is described as mixed with both batch and continuous elements. The weekly output of products is 50 to 500. The blinds are custom made to different dimensions. Company B has one type of product, blinds, but none of the blinds are identical, as every blind has different dimensions. This creates an extra level of complexity to the manufacturing. The level of changeovers is less than five per week and scheduling is performed weekly. Scheduling rules are applied and the scheduling is performed manually. The reason for this choice of scheduling approach as explained by the interviewee was that the company is very low tech. However, the company is moving towards an MRP/ERP approach. They have not considered scheduling software, although they say that they would be interested in scheduling software that is designed especially for their needs.

Company C

Company C is in the business of supplying automatic transmissions for the automotive industry. They have customers among all the major car companies. The production is described as continuous, with the weekly volume of a product being greater than 500. Company C manufacture more that 50 different variants and weekly volume of the main variant is over 500 products. It was not clear what the level of changeovers per week was. Scheduling is performed monthly using software developed specifically for Company C's needs and they were satisfied with this. They do apply scheduling rules, but have not looked at specific scheduling software available on the market.

Company D

Company D manufactures toothpaste and mouthwash for a number of different toothpaste brands. This is in the tradition of a cosmetic and medical product range, which means that clinical requirements are kept in place. The first impression of Company D is that they are well organised and have plenty of production performance measures in place. Information and data is continuously recorded on the shop floor and there are real time efficiency measures of the production lines.

Production process

- Paste making

  A thorough tour of the shop floor was given. Toothpaste is mixed in large industrial mixers. There are five of these paste processors dedicated for the *flexible site*, which is the part of the company site visited. After mixing, the paste is then transferred into 4-5 smaller "vessels". The vessels can take one ton of toothpaste. The vessels are then moved to the start point of the filling lines, where they are connected to the lines through pipes and valves. The paste is fed up to the filling machines. When a vessel is emptied, but there are more waiting, the vessels have to be changed over.
- Tube filling

  The filling of "stand-up" tubes was studied. The tubes have a bar code on them and as they go through the filling machine they are turned the right way so that when the tubes are closed on top, they are neatly closed with the text readable.
- Packaging

  There are two types of packaging for tubes that have been filled;

  1. The standard packaging. Tubes are put in single carton packages, thereafter 12 tubes are wrapped together in plastic and finally wrapped in cardboard.

  2. "The more environment friendly packaging" tubes are not packaged individually, but in a cardboard trays with a cardboard lid of either 12 or 18 in

each tray. No inner wrapping is used, hence saving packaging material. This packaging is for the German, Dutch and Scandinavian markets. The two box sizes of 12 or 18 tubes are dictated by the volume of the tubes, 75 ml or 95 ml. The volume size changes the height and diameter of the tubes, so machines are adjusted according to this. Boxes are automatically palletised and stored.

Scheduling and sequencing implications and considerations

Each line has a fixed twelve hour maintenance slot per week allocated and scheduled. If possible, however, planned maintenance tasks are carried out during changeovers occurring in the same week. Otherwise it is carried out during the allocated twelve hour slot. There are two meetings each day to coordinate the schedule. At this time the planning may change. The schedule may also change if a line breaks down. Furthermore, the shift manager can also change the schedule. Currently Company D is considering a fixed schedule applying repeating schedule and whether this approach would be possible. This means that if they have a sufficient forecast of the product demands they can decide a rigid schedule accordingly. For the *High Volume Site* this type of scheduling is being considered. However, where this interview was focused other options were being considered on the *flexible site*.

Sequencing was recognised as an important issue:
Example 1: A change may require the same tube, but a different paste.
Example 2: A change may require different tubes, but the same paste.

The company's view was that it is preferable to change the paste instead of changing the tube size. A changeover of tube changing the tube size can take anything up to eight hours. Changing both the paste and size of the tube may take up to twelve hours (there were examples where changeover had taken 24 hours).

The average speed of the line throughput is about 160 tubes per minute. However, because of breakdowns, changeovers, lunch etc, the throughput can go down to 50 tubes per minute. Sometimes a line may also run too fast and therefore run out of paste. When scheduling a new batch the average time (tubes/min) from historic records is used to set the cycle time. This average time is recorded by the on-line system.

Usually, Company D is given a two day Just In Time (JIT) window to deliver orders to their customers. However, there is no JIT integration of suppliers. Packaging components may arrive late, without any direct penalty to the supplier for late delivery. For JIT principles to work, aim would be to receive the tubes and cartons 48 hours before the filling process starts as the paste is usually available.

The scheduling horizon used is three weeks, which means that 3 weeks are planned in detail, and thereafter on every Monday, JIT scheduling takes place and changes may be done to the schedule.

The long term forecast is twelve months, scheduled monthly.

The medium term forecast is six weeks in weekly batches.

The short term forecast is to produce, and deliver daily.

When creating the schedules, past data is used to calculate the process/cycle times (number of products/min) using the last four weeks of data. Excluded from this are factors such as running out of paste and planned down time. Factors included are time available and actual production. This is calculated per day and the average is used. The disadvantage with this approach is that if the cycle times change it takes a couple of weeks before the change comes into place and then when this happens the rate may have changed again.

Company D measure 'The Internal Delivery Performance' and they calculate an 80% confidence interval of hitting the plan. Occasionally they apply *contingency SKUs* (Stock Keeping Units). This means that they over achieve, but if the market agrees to take on more products than was first planned this is okay, although not actually JIT production.

Company D apply a changeover matrix, *(CO Matrix)*, where the times of changing between different pastes and size of the tubes are described. If all the possible combinations of changeovers were included in this table, it would be a large and complicated table. This is probably one reason for its limited use. Secondly, the feeling is that the inconsistency of changeover times makes it difficult to maintain a matrix that is similar to reality. Questions here are; how good is the data and how much effort is needed to keep it up? Therefore, despite having such a matrix Company D use set values for changing between paste and paste, and tube and tube. Occasionally the *CO Matrix* is used, but in general a *CO Rule* is applied.

The CO rules states that:

Every time there is a paste changeover the standard time added is 4 hours.

Every time there is a tube changeover the standard time added is 4 hours.

This is an average especially as the maximum time for a paste change was known to be up to eight hours.

Company D apply what they call *"hard"* and *"soft"* scheduling rules. The rules for the main bases/pastes are hard. For instance, the flexible site always plans by paste first, preferring to change the paste base instead of the tubes. The next hard rule is to change the size of the tubes (fill volume). Another hard rule is to apply the sum of the changeover time for paste plus tube. If this takes place in parallel the maximum sum or the minimum sum for paste plus tube can be used. A soft rule would be the flexibility of lines and moving the products between lines. For example, move the paste to a line already set-up for a particular tube volume.

There may be cases, when due to changeover and batch size, Company D chooses not to accept an order. For example, the line with most changeovers produces short runs, such as batch sizes of 50,000 for a smaller market. The minimum batch size is 4 tonnes (1 mix) and if all this paste cannot be used by 50,000 tubes, then this means the remainder has to be stored. The alternative is not to take the order.

Products will not always run on the same line and occasionally the same product will run on several lines. If it occurs that two lines are running the same products, this means that twice as many vessels are being used. Because there is a high utilisation of vessels, using several vessels for the same product was not seen to be good practice.

If the stock of a paste has a short "best before date" this stock may be brought forward to produce it before it is out of date. If there is low stock of a paste, this might be moved backward in order to try to avoid running out of paste. This means that the schedule may be driven by other factors than customer demand and changeover levels. Re-scheduling may also be necessary if the tubes have not arrived from the customer as planned.

It can be concluded that there are two different demands on the schedule. First, there is the supporting market that wishes to have smaller batches and customisation and second there is the supporting business centre that would like to schedule large quantities.

Scheduling system

Company D use a finite scheduling system called *Advanced Scheduling (version 5.1.9.)*, from *Infor* (Infor, 2006). The system generates the requirements for paste, taking into consideration changeover time and adding extra time for these activities. However, the system does not take into consideration run-up and run-down (i.e. performing below the steady state).

The *Infor Advanced Scheduling* system has an inbuilt algorithm for minimising changeovers, although the company tend not to utilise this. The reasons were that it takes hours for the computer to run this algorithm form scratch, and if given a head start, with the jobs lined up manually based on experience, it takes about 20 min. This is still rather long to wait and then realise something needs adding and having to start over. There are also other algorithms inbuilt, such as scheduling for JIT etc.

The scheduling system is good in the sense that if a job is added to the schedule it adds a changeover to it. (This is shown in white colour on the schedule). If something is moved on the schedule the changeover time is moved around with the job.

There are no performance measures incorporated in the scheduling system and there is no feedback going back into the scheduling system regarding, for example, if due dates have been met.

Dealing with Changeovers

A marking system for change components is in use. All parts with yellow labels have change elements for different number of parts. Because Company D uses a twelve hour shift pattern, changeovers take place whenever they are necessary. Although, line changeovers are planned to be done by all three line personnel (1 line leader, 1 technician, 1 operator), in reality changeovers are often only carried out by the technician due to other demands. As a result the standard operating procedures are hard to follow.

In the high volume site (main plant) there are fewer changeovers. In this case the paste in the system may be left in situ and no cleaning is performed. In the flexible site changeovers are performed frequently, i.e. 3-4 changeovers/line/week.
A changeover of PASTE consist of:

- Disconnecting the PPV (Vessel)
- Disconnecting the pipe work
- Disconnecting the filler head
- Clean all three
- Add the new vessels, pipe work and filler head
- Sanitise the new product
- Get it checked and passed requirements
- Reconnect
- Blend through, so there is no air in the system (run-up)

In addition to this there is the process of changing tubes, when this needs to be done.

<u>Run-up</u>

Changeovers take place when the line is stopped, whereas filling the tubes many involve run-up problems and run-up is something Company D suffers from. A problem related to run-up the consistency of the toothpaste. The toothpaste could be to viscous, not runny enough etc. The run-up time is measured when toothpaste changeovers are performed. A changeover is defined as finished only after the line efficiency reached is 50% or above for the time of 15 minutes or longer (steady state).

<u>Cleaning</u>

In the cleaning process caustic soda is pumped through the pipes. The cleaning process strongly depends on which paste type the change is *from* and which paste type the change is *to*. It can take up to eight hours to complete the cleaning. If the same product is being produced on the same line over and over, cleaning does not need to take place very often, it can be left for months and months. If the changeover is from *active fluoride paste* to *non-fluoride paste*, cleaning is essential.

Changeover Recording Forms

Company D record which paste they are going from and which paste they are changing to for the changeovers. They have put in practice a *changeover sheet*, which is filled out at each changeover. There was resistance at first regarding this form, but it has now been accepted. They have done this for 5-6 months and have kept every sheet. They record each step in the changeover process, what has been done, who has done it etc. On the back sheet is a page for general input. The team/operators are then given feedback about what is reported on the changeover form. The last question on the form is "How long did it take to reach 50% line efficiency in a 15 minute period after the changeover (i.e. after the first good pack)?" This is a way of measuring run-up. The interviewee pointed out that a longer set-up may result in a shorter run-up time. The changeover (CO) forms are collected for each respective line and are checked by a Continuous Improvement Engineer and feedback is given to the line personnel. If problems occur during the changeover, these are discussed with the line personnel and appropriate actions are agreed.

Company D aim to develop improvements in order to try to reduce the changeover time, but they do not want to reduce it so that when production starts running, the run-up time increases.

Breakdowns and maintenance

There are different unplanned stops to the lines:

1. A stop shorter than 40 seconds is recorded as *inefficiency*
2. A stop between 40 seconds and 15 minutes is recorded as a *short stop*
3. Any stop longer than 15 minutes is recorded as a *breakdown*

An example of a stop could be a tube that has jammed in the machine. A long stop (breakdown) could for instance be a breakdown of the gear box. The improvement focus is on removing the short stops. There is often more frustration about many short stops rather than one big stop (breakdown). All stops are measured/recorded by the on-line system as well as stops for breaks and lunch. When stopping the machines a box pops up on the computer screen and information about the stop is recorded here, so for lunch hour, lunch would be recorded. There is also a maintenance board on the shop floor which is used to visualise maintenance needs. Necessary maintenance is now visible to everyone in the same place, before maintenance information was kept next to each machine. The technician of the line performs maintenance of the line, whereas the cleaning process is performed by the operator, which does not require special skills.

Company E

Company E performs testing of electronic equipment. The product range varies from very large electronic systems down to smaller products, such as mobile phones. Tests are performed that ascertain the electronic functions of the equipment. Other testing also performed includes environmental testing, such as heat or humidity tests, as well as vibration testing. The facilities are arranged such as in a job shop with elements of parallel facilities, hence can be described as a flexible job shop. Most jobs are "one-batch jobs" meaning one product to be tested is routed through the shop as a single product. Occasionally two or more product samples may be sent from the customers to be tested, this occurs if, for instance, a test is destructive. Jobs may take different routes through the shop and visit one or several types of testing facilities. Every new job (batch) needs a new changeover as Company E does not attempt to group products into similarities. Nor do they consider whether products require the same testing and hence similar routing through the shop. Company E schedules according to the heuristic FCFS (First Come First Served), as they consider it a fair rule towards their customers. They apply a manual scheduling principle by using spreadsheets in Excel, where the testing is scheduled in "1 day blocks" (8 hours or one shift). The company is using an ERP approach in other areas of the business, but has not incorporated a scheduling module.

5.3.7 Summary and choice of case study company

Company E was chosen for the main case study. Company E was considered to provide most to the research in terms of its extremes regarding changeable environment. Company E has a wide range of products, where each job is considered as one batch and where all jobs are looked upon as different from one another. This meant that with different scheduling policies the effect of product grouping could be investigated. The flexible job shop configuration gave opportunities for consideration of product routing. Changeover issues were highlighted by the company as important. Furthermore, their manual approach to scheduling offered inadequate flexibility and responsiveness, especially as Company E works in an area with fluctuations in demand. Finally, the company could assist with real data for a real problem.

The next chapter, Chapter 6, outlines in detail the in-depth case study data collection from Company E. In this chapter, Company E has been re-named TC (Testing Company).

CHAPTER 6 CASE STUDY DATA COLLECTION

6.1 INTRODUCTION AND BACKGROUND OF CASE STUDY COMPANY

This chapter outlines the information and data collected at the main case study company. As mentioned in the previous section Company E was selected as the main case study company. Henceforth Company E is referred to as TC (Testing Company) to reflect the fact that the company tests electronic equipment. This chapter gives a general description of the company and its processes and specific details of utilisation of facilities, processing times, changeover times and the product data collected for use in the simulation models. Current scheduling practices and planning implications at TC are discussed. All assumptions made during data collection and model building, are also listed.

The case study company is a company that runs product safety investigations and tests electronic and other products before they are released to market. TC offers among other tests and services, compliance solutions for a range of products, certification services for the radio and telecom market, and vibration and climatic testing.

TC's test site handles a large variety of products with different routing patterns through different facilities. The equipment at the TC site is shared between the various jobs in process, a feature typical of a job shop machine configuration. Thus, TC's test facilities can be characterised as a *job shop*. The test site also has certain parallel facilities, as for some testing there is a choice of several facilities. A job shop with parallel facilities is characterised as a *flexible job shop (FJc)* (Pinedo, 2002, p. 15).

6.2 CURRENT SCHEDULING PRACTICE AT CASE STUDY COMPANY

Planning and scheduling is currently performed on Microsoft Excel spreadsheets. A different scheduling spreadsheet is maintained by each department within TC. There are eight different scheduling plans plus one plan for offsite testing. Data regarding utilisation of facilities, processing times and arrival rates of jobs has been calculated from those spreadsheets for this research.

It is common that customers phone TC to see if their product(s) can be tested almost immediately, as testing and certification is often the last stage before products can start to be manufactured. However, it is not realistic to book a job in with such short notice. Before a booking is made the sales office and the project engineer will establish the testing requirements. The project engineer will then ask the planner in each department to assign the job to the schedule and book the facilities needed. This results in a planning horizon of about a month. Everyone can view the plans and at least two people in each department are assigned to add and amend the schedule.

According to this booking system jobs are assigned on a first come first served (FCFS) manner. Prioritisations will not be made, for instance the FCFS policy will not be overridden to allow a major customer to be scheduled before a less important customer.

Jobs may go between the different departments. However, this data is difficult to establish from the schedules as job numbers are not always given and there is no information on the spreadsheet where jobs will go to next. Departmental schedules are not integrated even though products are scheduled through more than one department. However, a study of jobs from a main customer MC took place and certain common job routes were established. Consideration was given to the testing sequence for example a test that will destroy the product should come last if only one sample is provided.

One job is considered as one batch and job splitting does not take place. Occasionally, customers may send several products to be tested. However, they are still considered as one job or batch.

The production plans were not very detailed. For example, everything is booked in blocks, where a block is one full eight hour shift. The smallest unit that can be booked is half a shift (4 hours). Furthermore, there is no data on what part of the booking is actual testing time and what may be equipment failure, changeover time, calibration of equipment etc. The issue of changeover times is solved later on by estimation of set-up times and by applying different levels of changeover reduction to the simulation model.

It is common for products to fail the testing, which may lead to delays and late jobs. There is no data available on the number of late jobs, but it is known that about 50% of all jobs fail one or more of their tests. Some jobs can be prevented from being late, as TC has a committed and flexible work force, where employees will work overtime or shift work when necessary. Figure 6.1 to 6.4 show photos of testing equipment and facilities at TC.

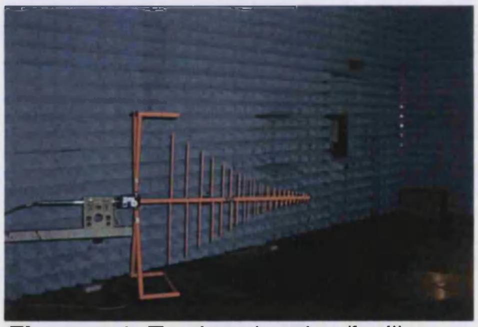


Figure 6.1: Testing chamber/facility and equipment.

Figure 6.2: Storage of test equipment when not in use.

Figure 6.3: Example of test equipment.

Figure 6.4: Example of environmental facility.

6.3 DATA COLLECTION

6.3.1 Availability of data

Data collection and the establishment of utilisation and processing times of facilities have been calculated using the Microsoft Excel spreadsheet that each department maintains. The main data set covers data from the whole of 2003 and the first six months of 2004. Because the 18 facilities studied belong to different departments within TC and hence have different schedules, the data set was not as large for certain facilities as for others. For five facilities the data set is for year 2003 only and for one of the facilities the data has been gathered from a span of six months. For five of the facilities, named O1, O2, C, P and I no data was available (section 6.3.2). This is because O1 and O2 are offsite facilities that are used when TC outsources a test for a product. No data is kept on the precise processing times and the utilisation levels of the outsourcing company. C, P and I facilities are services rather than a physical facility. Thus, no data is kept on processing times and utilisation of these activities. Values for O1, O2, C, P and I are therefore estimated to achieve a utilisation of about 80%. Table 6.1 indicates the availability of data. All estimated data was validated by company personnel.

Facility	Availability of data
F5	January 2003 - June 2004
F1	January 2003 - June 2004
F2	January 2003 - June 2004
T1	January 2003 - June 2004
T2	January 2003 - June 2004
S1	January 2003 - February 2004
S2	January 2003 - February 2004
O1	Estimated
O2	Estimated
C	Estimated
P	Estimated
I	Estimated
F8	January 2003 - June 2004
R1	January 2003 - February 2004
R2	January 2003 - February 2004
R3	January 2003 - February 2004
L	November 2003 - April 2004

Table 6.1: Availability of data.

Regarding the establishment of product data, such as product routing, a study of products from TC's major customer was carried out. This company is named MC, for Major Customer, in this thesis. In year 2003, MC bought 53% of the total services available (TC internal report, autumn 2004), from the part of TC's testing facilities that has been modelled in this study. Consequently the data gathered from MC's products is a large and representative part of the product mix. As mentioned, TC offers a range of testing services and has a large testing site, including about 50 test facilities and services. It is however common for customers to buy certain services and not all tests are needed for all types of products. Hence, this particular study has focused on the 17 facilities or services, used to test the MC's products.

6.3.2 Overview of facilities

Table 6.2 included below gives an overview of each of the 17 facilities or services that have been studied and incorporated in the simulation model. The facilities have been given abbreviated names such as F5 (Facility 5). The abbreviated names will be used throughout the thesis in the model building, experimentation and results sections. The word "Facility" used in Table 6.2 and throughout the thesis can represent either a testing facility or area where an actual *test* on a product takes place or a *service*, for example, the certification of a product.

<u>ElectroMagnetic Compatibility</u>

The concepts of emission and immunity testing are used in the description of some of the facilities. ElectroMagnetic Compatibility (EMC) is the ability of a product to operate within its intended electromagnetic environment and to accept or emit radio frequency (RF) disturbances within defined limits of the electromagnetic spectrum. Broadly EMC testing can be categorised into two areas; electromagnetic *immunity* and *emissions* testing. Electromagnetic immunity is the ability of a product to accept disturbance, and emissions testing is the level of disturbance produced by the product.

<u>Specific Absorption Rate (SAR) testing</u>

SAR testing indicates the amount of radio-frequency energy absorbed into human tissue by a radio transmitter. This test is performed for mobile phones and it tests the amount of radiation into a human head or body. (Continuing public concern about the health effects of body-worn radio transmitters together with changing legal requirements around the world have led to a need for increased activity in the field of SAR Testing.)

Designation	Description or facility or service
F5	Facility 5: Radiated emission testing. Among the facilities investigated, Facility 5 is the only one where radiated emission can be done, hence Facility 5 is highly utilised and is run with shift work.
F1	Facility 1: Immunity testing. Predominantly non-radio based products.
F2	Facility 2: Immunity testing.
T1	Test Hall 1: Bench testing for immunity. Immunity testing can be done in screened rooms, but also in a test hall on a bench. Other tests that take place in this facility are transient and surges.
T2	Test Hall 2: Bench testing for immunity. Immunity testing can be done in screened rooms, but also in a test hall on a bench. Other tests that take place in this facility are transient and surges.
S1	SAR Facility 1: Specific Absorption Rate (SAR) testing.
S2	SAR Facility 2: Specific Absorption Rate (SAR) testing.
O1	Offsite Facility 1: Predominantly within radio testing e.g. Radio Base Stations. When there are no test facilities or not enough capacity within TC to perform certain tests, those tests are then outsourced to an offsite facility.
O2	Offsite Facility 2: Predominantly within radio testing e.g. Radio Base Stations. When there are no test facilities or not enough capacity within TC to perform certain tests, those tests are then outsourced to an offsite facility.
C	Compliance of systems. Checking that the product complies with relevant safety requirements, before it is allowed on the market.
P	Product certification service.
I	International Market Compliance (IMC). Regulatory Compliance for a wide range of industry sectors. Also test for approval / conformance processes.
F8	Facility 8: Immunity testing, predominantly for radio based products.
R1	Radio Lab 1: For example, radio frequency (RF) testing, power testing and products are tested so that they do not interfere with other appliances.
R2	Radio Lab 2: For example, radio frequency (RF) testing, power testing and products are tested so that they do not interfere with other appliances.
R3	Radio Lab 3: For example, radio frequency (RF) testing, power testing and products are tested so that they do not interfere with other appliances.
L	Climatic Facility: Part of environmental department. Simulate climatic conditions, such as extremes of temperature, altitude, humidity, temperature cycling, solar heating and corrosive atmospheres. The climatic testing of products helps ensure the products will function in their intended environment.

Table 6.2: Overview of facility and services studied.

6.3.3 Utilisation data for facilities

Utilisation was calculated by studying the existing schedules and counting the number of days where testing had taken place. This value was then divided by the number of days available for work for each month. One facility, namely F5, is run with two shifts for seven days per week. Hence, weekends are considered as work days for F5. However, for all other facilities, weekends are not working days. Holidays, such as Christmas, are not considered as work days for any of the facilities. A working week, for all facilities except F5, consists of five days, Monday to Friday with one eight hour day shift for all of them. According to this the available number of work days per month is as displayed in Table 6.3 to 6.6. The actual work days (real data) are used, hence Table 6.3 to 6.6 show the precise number of work days that actually took place.

Month of year 2003	No. of days per month	No. of work days per month
January	31 Days	22 Work days
February	28 Days	20 Work days
March	31 Days	21 Work days
April	30 Days	20 Work days
May	31 Days	20 Work days
June	30 Days	21 Work days
July	31 Days	23 Work days
August	31 Days	20 Work days
September	30 Days	22 Work days
October	31 Days	23 Work days
November	30 Days	20 Work days
December	31 Days	18 Work days
Total Year 2003	**365 Days**	**250 Days**

Table 6.3: Work days year 2003, 1 shift.

Month of year 2004	No. of days per month	No. of work days per month
January	31 Days	21 Work days
February	29 Days	20 Work days
March	31 Days	23 Work days
April	30 Days	20 Work days
May	31 Days	19 Work days
June	30 Days	22 Work days
Total ½ Year 2004	**182 Days**	**125 Days**

Table 6.4: Work days year 2004, 1 shift.

Month of year 2003 for F5	No. of days per month	No. of Shift 1 Day per month	No. of Shift 2 Night per month	Total no of shifts per month
January	31 Days	30 Shift 1	30 Shift 2	60 Shifts
February	28 Days	28 Shift 1	28 Shift 2	56 Shifts
March	31 Days	31 Shift 1	31 Shift 2	62 Shifts
April	30 Days	26 Shift 1	26 Shift 2	52 Shifts
May	31 Days	29 Shift 1	29 Shift 2	58 Shifts
June	30 Days	30 Shift 1	30 Shift 2	60 Shifts
July	31 Days	31 Shift 1	31 Shift 2	62 Shifts
August	31 Days	30 Shift 1	30 Shift 2	60 Shifts
September	30 Days	30 Shift 1	30 Shift 2	60 Shifts
October	31 Days	31 Shift 1	31 Shift 2	62 Shifts
November	30 Days	30 Shift 1	30 Shift 2	60 Shifts
December	31 Days	24 Shift 1	24 Shift 2	48 Shifts
Total Year 2003	**365 Days**	**350 Shifts**	**350 Shifts**	**700 Shifts**

Table 6.5: Work days year 2003, 2 shifts for facility F5.

Month of year 2004	No. of days per month	No. of Shift 1 Day per month	No. of Shift 2 Night per month	Total no of shifts per month
January	31 Days	30 Shift 1	30 Shift 2	60 Shifts
February	29 Days	29 Shift 1	29 Shift 2	58 Shifts
March	31 Days	31 Shift 1	31 Shift 2	62 Shifts
April	30 Days	26 Shift 1	26 Shift 2	52 Shifts
May	31 Days	29 Shift 1	29 Shift 2	58 Shifts
June	30 Days	30 Shift 1	30 Shift 2	60 Shifts
Total Year 2003	**182 Days**	**175 Shifts**	**175 Shifts**	**350 Shifts**

Table 6.6: Work days year 2004, 2 shifts for facility F5.

Occasionally work takes place at weekends (as overtime) in one of the facilities other than F5. However, this does not happen frequently or often. It would also only usually happen to cope with special case problems elsewhere in the system (extraordinary equipment failure for example). Hence, the assumption has been to exclude this in the model and when calculating the utilisation.

As mentioned earlier, data for five facilities were not available and was therefore estimated. Those are facilities O1, O2, C, P and I. The utilisation was estimated to be 80% for all five facilities, as this was expected to be a comparatively high utilisation for this job shop. It was considered an advantage to test the heuristics against a high utilisation, rather than one which was too low.

In the real system immunity testing can take place in both Facility 1 and Facility 2. However, when studying the schedules, the product mix for F1 and F2 was different; compared to F1, F2 focused on larger processing times. For the conceptual model and the simulation model F1 and F2 are assumed to be parallel, with a similar product mix. Hence, in the conceptual model it is assumed that facility F2 takes on the characteristics of F1, as regard processing times and utilisation.

At TC there are two parallel S facilities (S1 and S2). However, on the schedule there is data available for only S1. This is because S2 is a new facility. It is therefore assumed that that the utilisation for S2 is as calculated for S1. This is an optimistic assumption, although the intention is to reach a high utilisation of both S1 and S2. Hence, it is important to test the scheduling approaches on a high utilisation.

The result of the utilisation calculations are shown in Table 6.7 and Table 6.8. Figure 6.5 shows a plot of the average utilisations for each facility. For a table detailing the utilisations over each month, refer to Appendix C (please refer to attached CD-ROM).

Facility	Utilisation
F5	78%
F1	70%
F2	70%
T1	61%
T2	46%
S1	80%
S2	80%
O1	80%
O2	80%

Table 6.7: Utilisation table 1.

Facility	Utilisation
C	80%
P	80%
I	80%
F8	73%
R1	51%
R2	60%
R3	39%
L	76%

Table 6.8: Utilisation table 2.

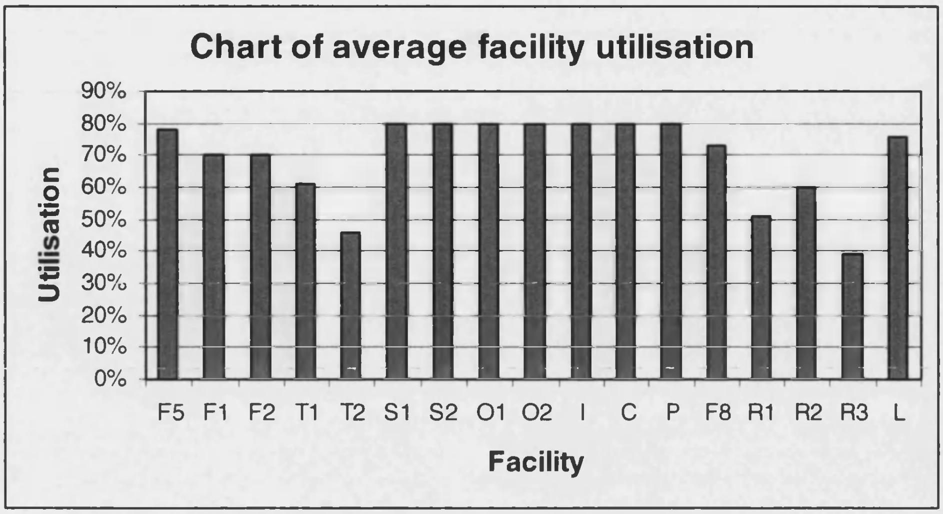


Figure 6.5: Chart of average facility utilisations.

6.3.4 Processing times for facilities

As described, processing times for each facility were gathered from the Microsoft Excel spreadsheets, using blocks of eight hours. A job may need processing (testing) from one day up to several days and occasionally a job is booked for weeks in certain facilities. To establish processing times, the schedules were studied and for each facility processing times for each job on the schedule were calculated.

As mentioned above only one of the two parallel facilities S is included on the schedule. The cycle time calculated for facility S1 is therefore applied to S2 as well.

Facilities F1 and F2 are parallel facilities that should have similar processing times when they are used for similar types of testing. However, on the schedule F2 has comparatively larger processing times than F1. The product mix studied with data from customer MC is more representative for facility F1, with shorter processing times. Hence, in order to balance the two facilities the processing times from F1 are applied to both F1 and F2.

In order to achieve the same processing times for parallel facilities, as this would show that the same type of testing would take the same amount of time, the processing times for T1 and T2 are summarised and the average is applied to both of these facilities in the simulation model. Furthermore, R1, R2 and R3 processing times are summarised and the average is applied to all three facilities in the simulation model.

The distributions of processing times for each facility are plotted in Figures 6.6 to Figure 6.12. In the simulation model the processing times have been modelled as user defined distributions in line with these graphs. For details on processing times and ranges of random numbers applied in the distributions, refer to Appendix D (please refer to attached CD-ROM).

Figure 6.6: Processing time distribution for F5.

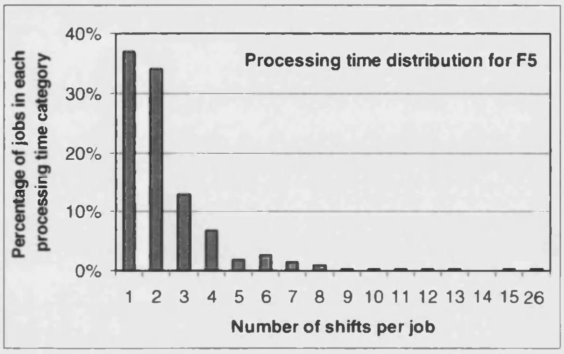


Figure 6.7: Processing time distribution for F1 and F2.

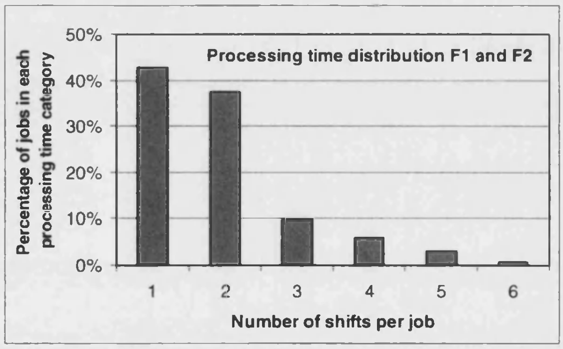


Figure 6.8: Processing time distribution for T1 and T2.

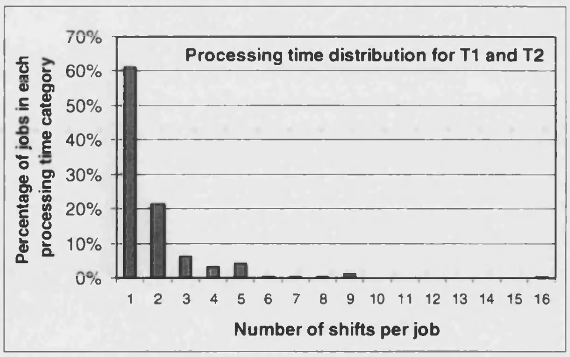


Figure 6.9: Processing time distribution for S1 and S2.

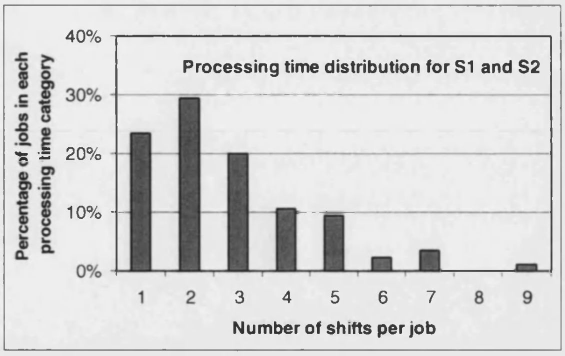


Figure 6.10: Processing time distribution for F8.

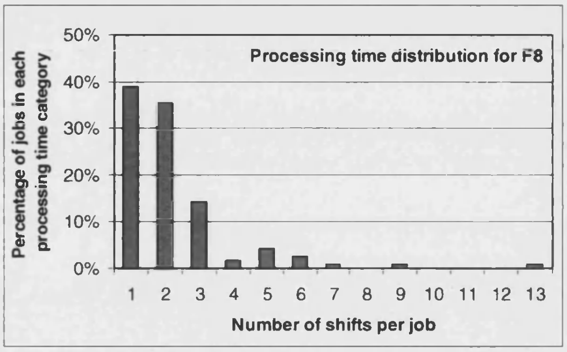


Figure 6.11: Processing time distribution for R1, R2 and R3.

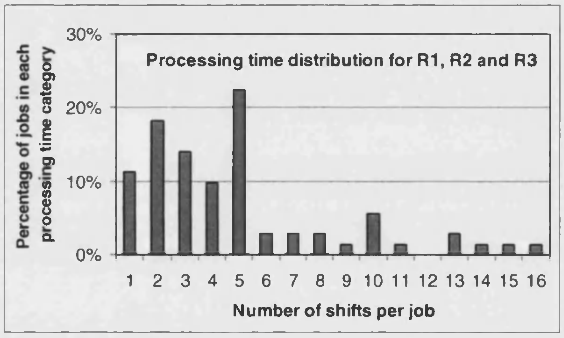
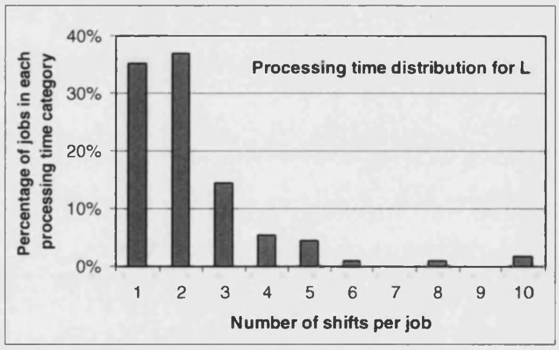


Figure 6.12: Processing time distribution for L.



For the utilisation calculations, processing time data for facilities O1, O2, I, C and P were not available, hence estimates of processing times were made. O1 and O2's processing times were estimated as a 10 shifts (or the same as 10 days). This is a reasonable estimate as those are offsite facilities and jobs needs to be transported offsite, tested and then transported back to the TC site. For facilities I, C and P that are certification and compliance processes, processing times from four to nine shifts were assumed.

The times were validated by TC engineers. The estimated processing times were also coordinated, so that the facilities reached the desired utilisation levels. Estimated processing times are shown in Figure 6.13 and Table 6.9.

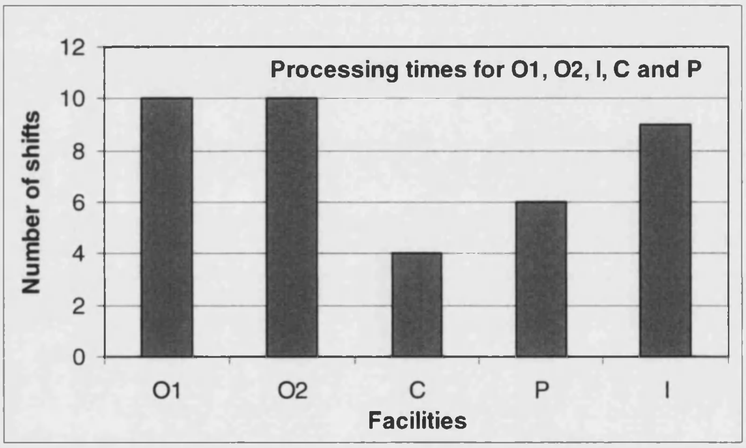


Figure 6.13: Processing times for facilities O1, O2, I, C and P.

Facility	Processing times (shifts)	Processing times (min)
O1	10 shifts	(10 shifts*480min) = 4800 min
O2	10 shifts	(10 shifts*480min) = 4800 min
C	4 shifts	(4 shifts*480min) = 1920 min
P	6 shifts	(6 shifts*480min) = 2880 min
I	9 shifts	(9 shifts*480min) = 4320 min

Table 6.9: Processing times for facilities O1, O2, I, C and P.

6.3.5 Product data from Major Customer (MC) products

As mentioned above TC's major customer MC buys around 50% of the testing services capacity from TC. Hence, data from the MC product range has been collected to represent a major part of TC's product mix. The MC products studied go through different numbers of tests and different combinations of tests. The MC products were categorised in to *product families* and *sub-product families* according to the test procedures they required. This resulted in five product families and 18 sub-product families. The *product family* was characterised by the number of test operations the job required. This had an impact on the total process time which increased with the number of operations. Each product family was represented by a number of *sub-product families* (jobs with identical characteristics) belonging to it. For the job shop a total of seven operations were identified namely; α, β, γ, δ, ε, ζ and η. Table 6.10 lists, each product family, the job families associated with these and the operations for each sub-product family.

Each *operation* can consist of a different number of facilities or *sub-operations* as shown in Table 6.11. For a job to belong to a particular family the same types of tests and the same processing routes were required. This assumes that there was one specific route for each of the 18 sub-product families studied. These routes included a number of sub-processes consisting of one or more operations (a stop at one facility). For example, sub-product family A51 consists of five operations (αβγδε) and a total of eight sub-operations (3 at α, 1 at β, 2 at γ 1 at δ and 1 at ε) as specified in Tables 6.10 and 6.11, i.e. type 'A51' jobs will be tested at eight facilities. Due to the number of operations and sub-operations the issue of changeover was investigated to ascertain the impact on the sequencing and scheduling of the jobs. The product routing is displayed in Figure 6.14, where each "square" represents one operation and jobs can go through one or up to five of those operations. It is worth noting that facility F8 is used both for operation γ and operation η.

Product Family	Sub-Product Family	Operations for each Sub-Product Family
A	A51	αβγδε
B	B41	αβδε
B	B42	αβγζ
B	B43	αηδε
B	B44	αβηζ
C	C31	αβδ
C	C32	αβζ
C	C33	αηζ
C	C34	αβη
D	D21	αβ
D	D22	αγ
D	D23	αη
D	D24	αζ
E	E11	α
E	E12	β
E	E13	ε
E	E14	δ
E	E15	η

Table 6.10: Product families and sub-product families for MC products job mix.

Operation (O)	Sub-Operation (SO)
α	F5 + (F1 or F2) + (T1 or T2) = **3 SO**
β	(S1 or S2) = **1 SO**
γ	(O1 or O2) + F8 = **2 SO**
δ	C = **1 SO**
ε	P = **1 SO**
ζ	I = **1 SO**
η	F8 + (R1 or R2 or R3) + L= **3 SO**

Table 6.11: Operations and sub operations for MC products job mix.

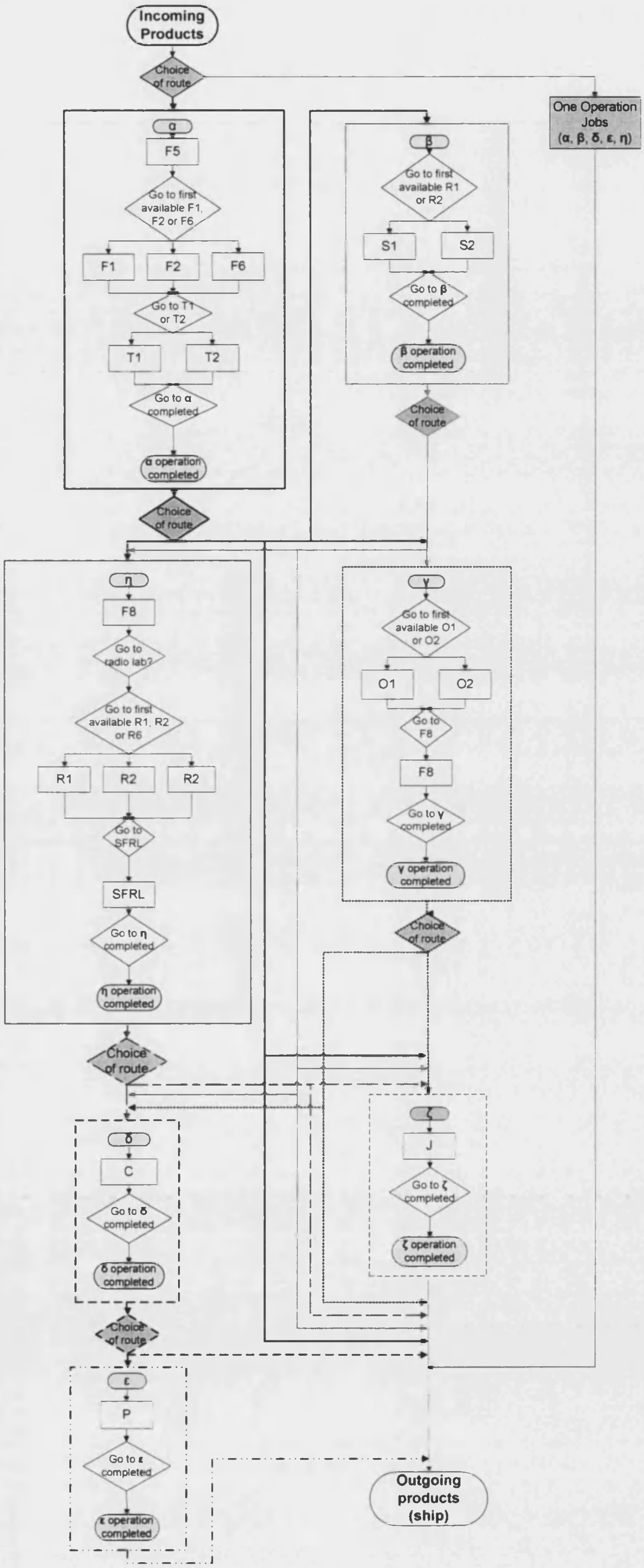


Figure 6.14: Operations and sub-operations for MC products job mix.

Processing time comparison of MC jobs and all jobs

The processing times for the MC jobs for each of the 17 facilities were calculated in the same manner as the processing time had been calculated for all jobs (section 6.3.4). This was done so that it could be established that the MC jobs were representative as a sample of all jobs regarding processing times. The comparative graphs of MC processing times and all processing times at each facility are displayed in Figure 6.15 to Figure 6.21. As can be seen from the graphs, the distribution of processing times for the subset of MC products matches the overall processing times well.

Figure 6.15: F5 - Comparison of processing times All Jobs and MC Jobs.

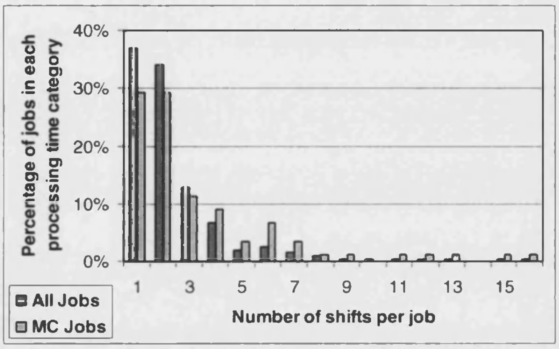


Figure 6.16: F1 and F2 - Comparison of processing times All Jobs and MC Jobs.

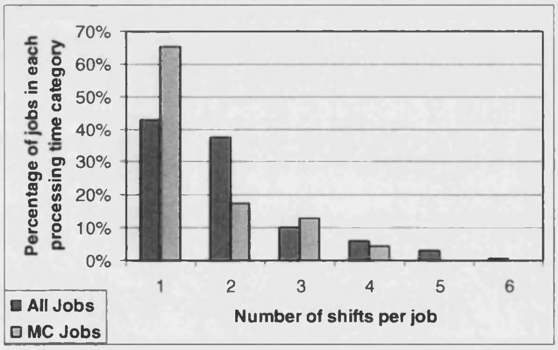


Figure 6.17: T1 and T2 - Comparison of processing times All Jobs and MC Jobs.

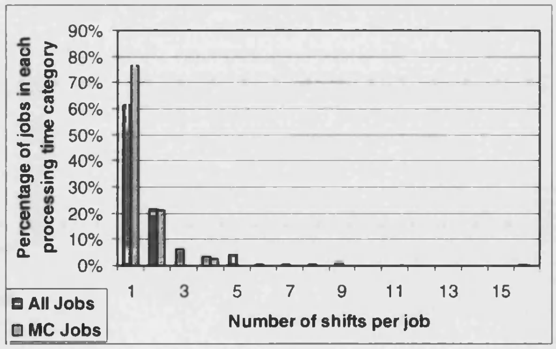


Figure 6.18: S1 and S2 - Comparison of processing times All Jobs and MC jobs.

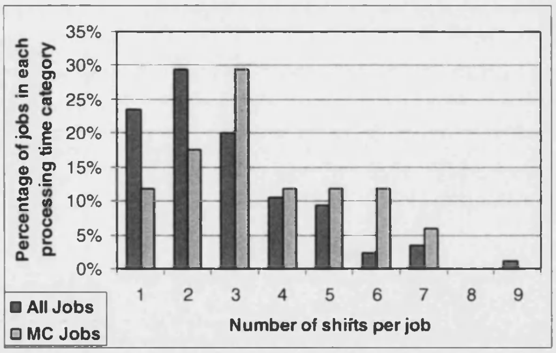


Figure 6.19: F8 - Comparison of processing times All Jobs and MC Jobs.

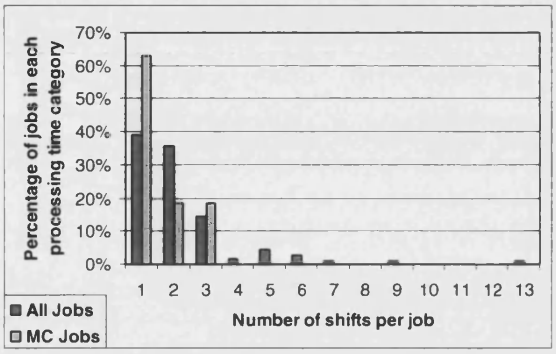


Figure 6.20: R1, R2 and R3 - Comparison of processing times All Jobs and MC Jobs.

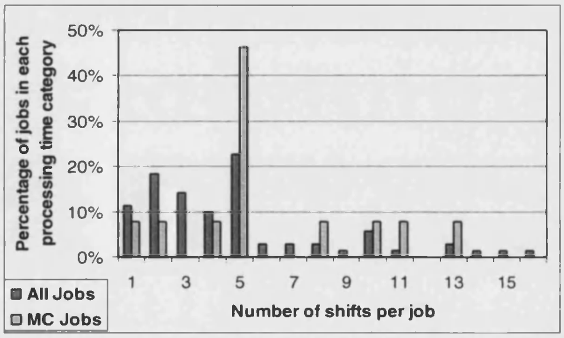
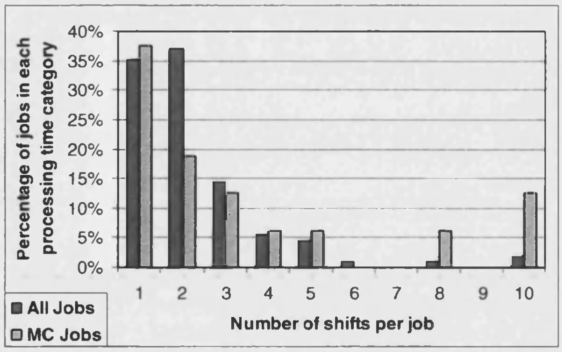


Figure 6.21: L - Comparison of processing times All Jobs and MC Jobs.



6.3.6 Changeover times for facilities

The main focus of this research has been to investigate changeover sensitive scheduling rules and the effect these can have on changeover time reduction. Hence, it was of interest to look at changeover times at TC. However, because there was no numerical data on changeover times recorded at TC it was decided to investigate possible changeover time reductions and what effect those would have on the scheduling and sequencing, in particular regarding applying the concept of differentiating between products from different product families and sub-families.

Even though specific details of changeover times are not recorded, certain information regarding changeovers is known. Changeovers occur at each of the test facilities. A changeover takes place between every new job that is tested. This is a fact since it is known that testing equipment is always taken down and placed in an allocated storage area after every job is completed. When a new job is set-up the necessary equipment (e.g. amplifiers, cables etc.) is picked up from store and connected to the product to be tested.

<u>Structured method of modelling used in value stream mapping</u>

In order to find out more about changeover times and set-up issues value stream mapping was performed on a typical testing procedure at TC. Value Stream Mapping (VSM) (Bicheno, 2004) is a method of visually mapping a product's production path from "door to door". A *value stream* is all the actions (both value added and non-value added) required to bring a product through the flows essential to every product. One example is the production flow from raw material until the finished product delivered to the customer. In analogy with the testing process at TC this would be from a product arriving untested to completion of the required tests and certification issued so the customer can sell their product.

Figure 6.22 shows a possible changeover and testing procedure at TC. When testing is being planned at TC a block of one to any number of days is booked in the Excel spread sheets used for scheduling. The available schedules do not divide the testing procedures into, for instance, set-up time and take-down time. Instead everything is included in one block on the schedule. TC Figure 6.23 was drawn up before the value stream mapping took place as an example of what was perceived to occur during the testing. In Figure 6.22, the testing has been divided into a set-up and a take down activity, as well as the actual testing time. An activity named “customer interference” is also included as this may occur. Note that the distance and the relationship between the activities are only shown graphically and there is no time scale in the figure.

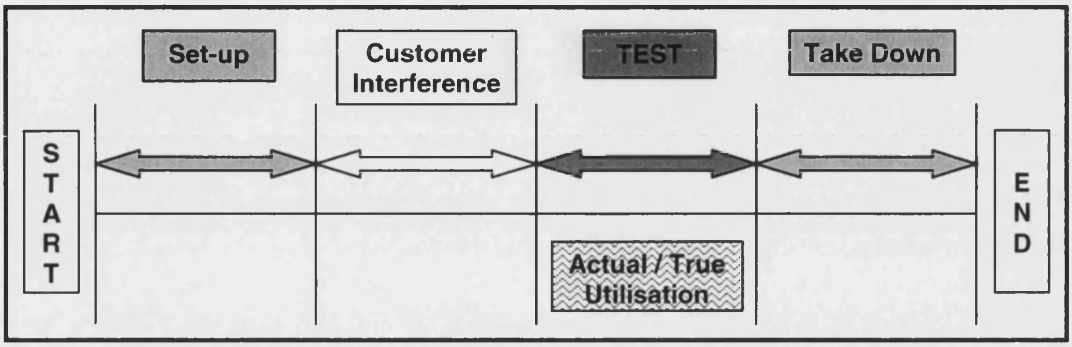


Figure 6.22: Example of possible changeover and testing activities at TC.

Value stream mapping example

Mapping of conductive emission testing was studied in order to establish different activities throughout the testing procedure. Present during the testing was the test engineer, a representative from the company whose product was going to be tested and the author of this research. Before the testing was started the researcher asked the test engineer to estimate how long he thought the testing would take. The estimation is visualised in Figure 6.23. Thereafter, the actual testing was studied and times for different activities were recorded. The result is shown in Figure 6.24. Figure 6.25 shows the actual testing to be twice as long as estimated.

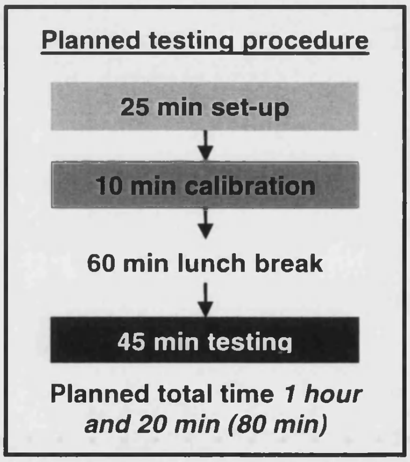


Figure 6.23: Planned testing procedure.

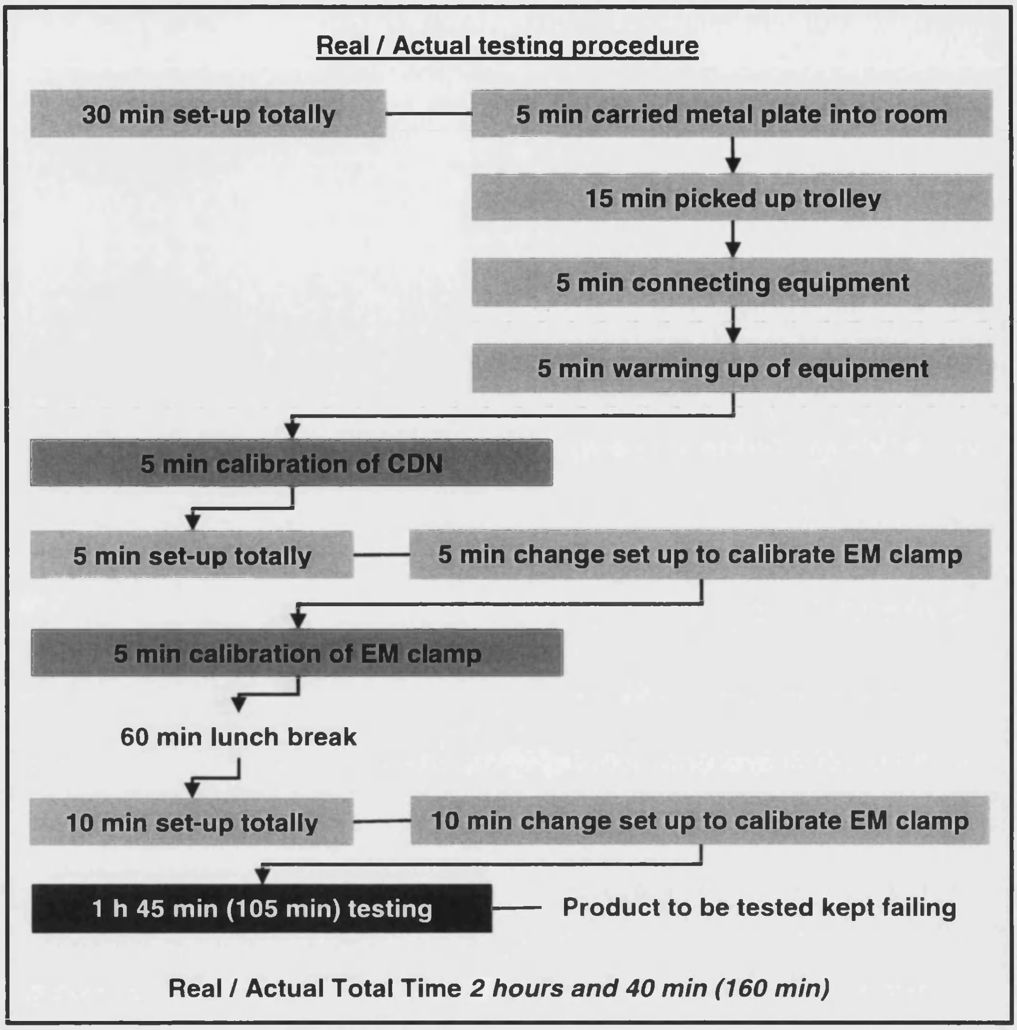


Figure 6.24: Actual testing procedure.

Extra Time
2 hours and 40 min (160 min) -
1 hour and 20 min (80 min) =
1 hours and 20 min (80 min)

Figure 6.25: Extra time for testing procedure.

As can be seen in Figure 6.24, compared to the estimated times in Figure 6.23, the total time of the activities are longer than estimated and the set-up time activities consisted of a set of different sub-activities than originally considered. It will be assumed that the calibration time is part of the set-up activity of changeover. This example of changeover and testing activities does not give a comprehensive picture of all testing activities at TC. However, it did give valuable insight into the testing process.

No policies to reduce changeover times were in use at TC when the data set was gathered, and it was therefore decided that it would indeed be interesting to investigate different levels of changeover time reductions and what effect this would have on the testing process. Together with representatives from TC possible levels of reducing changeover times were discussed. No precise data for changeover time was available. Hence, possible level of changeover time reduction was estimated in discussion with company experts at TC.

Figure 6.26 shows some of the testing equipment that was used in the value stream mapping example.

Figure 6.26: Testing equipment used in the example.

Minor and major changeover times

It was concluded that the changeover time between jobs varied depending on whether the change was between jobs from different product families or between jobs within the same product family. There is deemed to be a *major reduction* in changeover time if two jobs from the same *sub-product family* are tested in sequence. There is a *minor reduction* in changeover time if two jobs from different *sub-product families*, but from the same *product families* are tested in sequence. If a job is followed by a job from a different *product family* there is no changeover time reduction as it is assumed that a full changeover is necessary.

Naturally incorporating changeover time increases the total throughput time (process time and changeover time) of the job. The data gathered within this particular industrial sector indicated that the shorter the total throughput time for a job the longer the percentage changeover time tended to be. The total changeover time, as shown in Table 6.12, consists of set-up time, take-down (or run-down) time and internal set-up (adjustments). Internal set-up within this company is the set-up time that takes place between different test programs and the adjustment to the set-up during a test, e.g. changing positions of electrical cables.

Test time (no. of days)	Major changeover reduction between jobs within the same sub-product family	Minor changeover reduction between jobs within the same product family
1 - 4 day	33%	10.0%
5 - 9 days	25%	7.5%
10 - 19 days	20%	6.0%
20 - days	15%	4.5%

Table 6.12: Major and minor changeover time reduction.

6.3.7 Shift and working hours

As already described, Facility F5 has two shifts per day from Monday to Sunday. Each shift is eight hours, which adds up to 16 hours (960 min) work each day. One shift is a day shift and one shift is a night shift. F5 is the only facility that tests for radiated emission hence extra shift work is needed. All other facilities have one shift of eight hours (480 min) from Monday to Friday. Each shift includes additional time for lunch (30 min) and one 15 min break in the first part of the shift and another 15 min break in the second part of the shift.

6.3.8 Arrival interval and generation of jobs

In order to establish arrival rate of jobs and estimate the number of jobs that go through the shop the schedules were studied and it was determined how many new jobs were started each week. Figure 6.27 shows the distribution of new jobs over a thirteen week period. As can be noted most jobs start on Monday and the majority start from Monday to Thursday with one job starting on a Friday. However, no new jobs are scheduled to start on Saturday or Sunday. According to the graph the average number of jobs that start per week is 3.69 jobs. Multiplying this by 52 weeks per year gives a number of 192 jobs to start over the year.

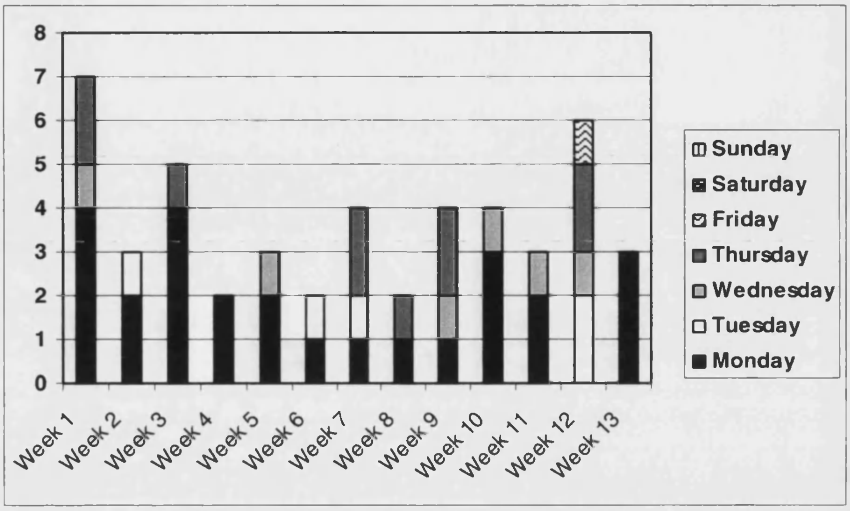


Figure 6.27: Arrival of parts distribution.

The numbers of jobs starting each week is conceptually different from the scheduling or planning horizon, as jobs may be planned about a month in advance and then start at some point during the month. One part of the research has investigated scheduling over different time horizons, such as weekly, monthly and yearly (Eriksson, 2005). However, it can be said that the actual planning horizon at TC is about four weeks.

6.4 ASSUMPTIONS MADE FOR SIMULATION MODEL BUILDING

When performing the initial testing scenarios and experiments with the simulation model (Chapter 7), it was realised that there were a large number of factors and parameters that could be varied throughout the experimentation. Possible parameters to study were for example: failure rate of products, re-testing implications, number and choice of dispatching rules, utilisation levels of the job shop, shift patterns, changeover times including run-up and take down, due date variation, processing times, buffer sizes, number of facilities, number of product families and job families, planning horizon, breakdowns, maintenance, human resources and equipment.

Furthermore, there was a lack of availability of detailed data that would require much time and effort to produce. The effort required to collect such data had to be considered against what would be feasible within the time frame of the project.

Therefore, in order to keep within the scope of the project, as well as within a reasonable time frame, assumptions regarding data collection and model building had to be made. Those assumptions are listed here.

- During normal operation the testing facilities cannot fail or breakdown, as they are physical rooms.
- There is no data on failure rate of equipment. However, when asking experts at TC, it seems that there is rarely a problem with equipment breakdowns that cannot be covered by spare equipment, hence failure of equipment was excluded.
- Regarding equipment used for testing, there are normally multiple resources available, such as several amplifiers. The assumption is therefore that necessary equipment is always available.
- Employees are flexible and multi-skilled, e.g. they can do different types of testing and are positive to overtime and shift work if required. It is therefore assumed that there is always an available engineer when a test is taking place in the model. Hence, human resources are not included in the model. It is considered more beneficial to focus on areas where problems are more apparent.
- Buffer sizes are set as unlimited in the model.
- Each facility tests one job at one time.
- There is no circulation of jobs within the shop. When jobs fail a test they may need to be retested. It is assumed in this study that when/if this occurs, the job is simply rescheduled and dispatched as a new job in the model.
- It is assumed that calibration time is part of set-up and changeover activities.

6.5 SUMMARY

This chapter has discussed the data collection and related assumptions that were made for the conceptual model and will be applied throughout the building of the simulation model.

It can be concluded that the testing facilities at TC can be characterised as a *flexible job shop*. In a job shop products are assigned pre-determined and different routes throughout the shop floor. A flexible job shop is an extension of the job shop where, one, several or all processes in the job shop have parallel processes. At TC several processes have parallel facilities. For a job shop with a high number of machines and a large product mix finding an optimal schedule can prove difficult, especially if sequence dependent set-ups are present.

There was a limitation of how much data could be feasibly collected during the timeframe of the project. However, processing times and utilisations of facilities were calculated using the available Excel spreadsheet schedules. Furthermore, product data from the major customer was collected and typical product routings through the shop floor were ascertained. This involved establishing operations and sub-operations of testing. Certain assumptions and estimates had to be made, such as changeover times. To overcome the lack of data in this area it was decided to apply possible reduction of changeover times, which was agreed in discussion with company experts at TC. Furthermore a range of levels of changeover time reduction were estimated for simulation. The arrival frequency of jobs was investigated and finally a list of further assumptions was created.

During the building of the simulation model it was occasionally necessary to include further assumptions and those are outlined in Chapter 7 as the process of model building is discussed. The simulation model was to provide a benchmark and use rules for assessing their performance on changeover reduction.

CHAPTER 7 MODEL BUILDING AND VALIDATION

7.1 INTRODUCTION

This chapter outlines the model building and the validation of the simulation model. The data collected and analysed as discussed in Chapter 6 has been built into a Witness simulation model. The model was then verified and validated against expected output of the real system. A sensitivity analysis of the parameter for due date setting has been performed. This chapter also includes a section where warm-up time, number of runs and run-length of the model have been determined for the experimentation. It should be noted that the validation and experimental design activities were ongoing throughout the model building and sometimes took place in parallel.

7.2 THE IMPORTANCE OF MODEL VALIDATION AND VERIFICATION

Before the details regarding validation and verification of the simulation models are presented, section 7.2 discusses these terms and explains the process of validation and verification within this project.

Verification and validation aim to determine the accuracy with which the model predicts the performance of the real system (Robinson, 2003 p. 209). The *verification* process is concerned with establishing that the model assumptions have been accurately programmed for the simulation model, whereas the *validation* process determines that the simulation model represents the real system (for the particular objectives of the study) (Law and Kelton, 2000, pp. 264-291). The concept of *accuracy* of a model is different from validity. Validity is a binary decision, while accuracy is measured on a scale of zero to 100% (Robinson, 2003, p. 210). Meaning a model is either valid or not, but it may be more or less accurate. A model cannot be completely accurate. Only the real system would have complete accuracy and a model can only reflect this in full if it is identical with the real system. In addition to this, a model can be explained as reflecting one point in time of the real system, whereas the real system continues to evolve over time. To reflect different situations of the real system, there might be several versions and different scenarios of a model. The reason for this could be to reflect different situations of the real system. A model has *credibility* if "managers" and key project personnel accept it as "correct" (Law and Kelton, 2000, pp. 264-291). Therefore, a credible model is not necessary valid and a valid model is not necessary credible.

The conclusion is that a model is a simplification of the real system, built to explore and understand the reality. Therefore the aim of validation is to ensure that the model is sufficiently accurate and the objective of the model must be known before it is validated.

Verification and validation is not always straightforward to perform and a number of problems can arise during the process (Robinson, 2003, pp. 209-225);

- There is no such thing as a general validity. This means that a model is only validated with respect to its purpose.
- There may be no real world to compare the model against. The model may have been developed for a proposed production facility or the model represents the existing system, but this does not mean that it is valid when it represents a changed system.
- Different people interpret the real world differently. For instance in a bank an employee at the bank and a customer may not see the world from the same angle.
- Often the real world data are inaccurate. Also "accurate" data may only be a sample, which creates inaccuracy.
- There is not enough time to verify and validate everything.

To summarise; proving that the model is valid in practice is not possible; instead the approach should be to think in terms of confidence in the model. Verification and validation are not processes to try to show that the model is correct, but rather processes of trying to prove that the model is incorrect (Robinson, 2003, p. 214).

Verification and validation of a simulation model is an ongoing process throughout the development of the model. Figure 7.1 shows the relationship between the main phases in this process.

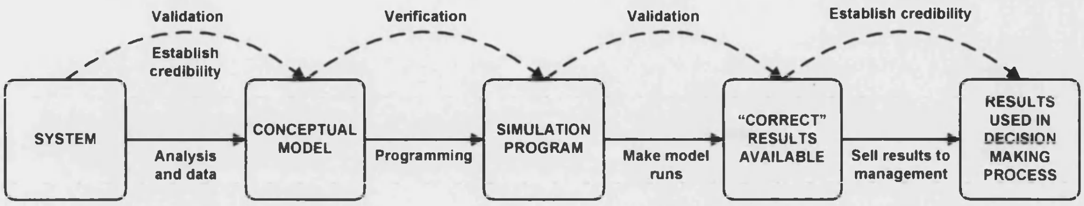


Figure 7.1: Validation, verification and credibility (Law and Kelton, 2000 p. 266).

The methods applied for validation and verification of the simulation model in this study utilise a combination of the recommendations by Robinson (2003, pp. 209-225) and Law and Kelton (2000, pp. 264-291).

7.3 VALIDATION AND VERIFICATION THROUGHOUT THE MODEL BUILDING

Debugging of the program code:

- The simulation software used in this study (Witness) utilises modular programming (Lanner, 2006). For instance, every machine being modelled has its own module to be programmed and every time a change is made to this module, debugging (verification) of the new code takes place, before any changes can be saved.
- The model was built in stages and each stage was verified separately. For example the different dispatching rules were modelled separately and then run with the model, so that the actual sequence of the jobs could be studied to certify that jobs were sorted as expected.
- For the product routing, visual verification was performed. Each sub-family was studied on its way through the job shop to determine that jobs took the correct route. The total processing time for each sub-family was also verified.
- The program code was reviewed by the researcher (main program developer) and by the two supervisors of the project. Furthermore, input from experts on Witness programming at the Witness helpdesk support was considered.

- The model was run with different processing times, different number of products and with products that have been generated in different manners. In addition to this, the model has been run for short periods and for longer periods of time. The outcome of these differences has been studied in order to determine that the models ran as expected.

Observations of the real system and expert discussions:

- The researcher gained an in-depth knowledge and understanding of the actual system, through company visits, interviews and observations of the real process, which has benefited the validation process.
- Information and data used in the model were obtained from documents as well as from machine operators, engineers, project managers, schedulers and managers at different levels. This has increased the accuracy of the simulation model.
- Data needed to be converted into a format that could be programmed in the simulation software. For instance, machine cycle time data was available in Microsoft Excel spread sheets, but was recalculated as distributions for each facility. This recalculated data was displayed in diagrams and validated with people at the company.
- During the development of the conceptual model and the simulation model, frequent discussions with subject-matter experts at the company as well as discussions with expertise at the university, took place (visits, phone calls and e-mails). Furthermore, the model was shown running to these experts, so that they could suggest changes and inputs. This increased the credibility of the model.
- Assumptions made were recorded as work progressed. The assumptions are discussed in Chapter 6. All assumptions were listed with logic and impacts and the reason for the assumptions were noted. The list of assumptions was discussed and agreed with the supervisors.
- The modelling process, rules, verification and validation were all discussed at regular supervisor/company meetings.

Data validation (For details of data collection and analysis refer to Chapter 6):

- Two data sets of processing time data were selected. The first set covered data for year 2003 and the second set covered six months of year 2004. These sets were analysed and compared and shown to be homogeneousness, therefore they could be merged.
- A comparison was also performed for the average processing times of all jobs included in the data available and the processing time for a certain smaller set of products where other data, such as product routing, was also available.
- Where data was unavailable estimations had to be made in discussion with subject matter experts at the company and with the project supervisors. The estimates made are clearly identified in Chapter 6. In addition to this, during the life-cycle of the project more data became available.

7.4 MODEL DESIGN AND BUILDING

During the model building and validation phase a range of different models were constructed and different modelling approaches tested. Finally, three major models were designed and different scheduling scenarios were applied to these. For full details of the programming code refer to Appendix H (please refer to attached CD-ROM). The three major models will be referred to as; Model 18, Model 42a and Model 42b.

- Model 18: This model is named 18 because there are 18 sub-families in this model. Model 18 has a product mix that is based on the product mix from the data collection of MC's products. As stated earlier MC buys testing services that covers about 50% of the service that TC sell. Hence it is reasonable to increase the number of MC products in the model to 100% and apply scheduling scenarios to this subset of products. When validating this model it was realised that the utilisations of the machines were not evenly distributed and dissimilar to the utilisations determined by the data collection (Chapter 6). For certain facilities utilisation was higher and for others utilisation was lower. This is shown in section 7.5. The reason the shop was not evenly balanced regarding utilisation was because by increasing the number of products from the subset of MC products a typical product mix was not reached. To improve utilisation levels another 24 products with a different mix of processing times were created and added to the model. This generated Model 42a.

- Model 42a: This model is named 42 because there are 42 sub-families in this model.
- Model 42b: This model is named 42 because there are also 42 sub-families in this model. The difference between Model 42a and 42b is that 42a applies the processing times for the facilities according to the processing times gained from the data collection (Chapter 6). However, Model 42b has processing times that are 1/10 of the original processing times. This model was created so that the scheduling principles could be investigated under different product processing conditions.

Each of the three main models are validated and discussed in parallel in the following sections of this chapter, but first the building and design of the models are discussed. Experimentation has taken place with all three models, so that results can be compared for different sets of parameters.

7.4.1 Categorisation of sub-product families and product families

Sub-product families are categorised in the same manner for all models. However, jobs have been categorised differently in product families for the different models. In Model 18, there are 18 sub-product families, and those have a number of operations that varies from 1 to 5, the assumption for this model has therefore been to say that jobs with the same number of operations are similar types of jobs, as they require similar types of testing. This is a fair assumption as the study of processing times (Chapter 6) has showed that processing times depend on the type of test rather than the actual product. This can be seen in Table 7.1, where it is shown that Model 18 has 18 sub-product families (named A51... to ... A15) and five product families (named 1, 2, 3, 4 and 5). On the other hand Model 42a and Model 42b have 42 sub-product families and four product families. This is because for these models the product families are categorised differently. In Model 42a and 42b it is assumed that the subset of products from MC belongs to the same product family. As well as increasing the number of products for MC products another three product families have been added, adding up to a total of four product families and 42 sub-product families. Product families in Model 42a and 42b have been named A, B, C and D. This can be seen in Table 7.2.

Product family	Sub-product family
1	A51
2	A41
2	A42
2	A43
2	A44
3	A31
3	A32
3	A33
3	A34
4	A21
4	A22
4	A23
4	A24
5	A11
5	A12
5	A13
5	A14
5	A15

Table 7.1: Product families used in Model 18.

Product family	Sub-product family
A	A51
A	A41
A	A42
A	A43
A	A44
A	A31
A	A32
A	A33
A	A34
A	A21
A	A22
A	A23
A	A24
A	A11
A	A12
A	A13
A	A14
A	A15
B	B51
B	B41
B	B31
B	B32
B	B21
B	B22
B	B23
B	B24
B	B25
B	B11
C	C31
C	C21
C	C22
C	C23
C	C24
C	C25
C	C26
C	C11
C	C12
D	D51
D	D41
D	D42
D	D43
D	D31

Table 7.2: Product families used in Model 42a and 42b.

The reason for testing different groupings of products is that it gives an additional aspect to the testing and experimental procedure. This means that the effect of different product configurations can be investigated (e.g. the impact of short and long processing times). The characteristics of Model 18's product families is that the jobs which have more operations, in general are longer jobs and the impact of length of total processing time can be studied. Certain characteristics have been incorporated also for the product families in Model 42a and 42b, where product family A (the MC subset) is a mix of jobs with longer and shorter total processing times. Product family B has a similar mix to A with jobs having one to five operation sub-product families, whereas product family C is a grouping with overall shorter jobs, one to three operations. Finally, product family D overall consists of jobs with several operations, either including five, four or three operations. Since there were no data regarding typical groupings at TC, it is interesting to test different categorisation and see what impact this may have on the results. Note that for Model 42b the product mix is the same but all processing time have been reduced by a factor of 10.

7.4.2 Increased number of operations for Model 42a and Model 42b

The product routing is based on products going through a number of operations and sub-operations. A sub-operation is testing in one facility and an operation is a combination of one or more of these sub-operations. For the MC sub-set of sub-product families there are *seven* operations (named α, β, γ, δ, ε, ζ and η). The MC sub-set is used in Model 18. The product routing for Model 18 is displayed in Figure 6.14. When building Model 42a and Model 42b another three operations (named θ, ι, κ) were added. This was a necessary addition as simply adding jobs with exactly the same operations as Model 18 did not fully deal with the imbalance in the utilisation (section 7.5) of the facilities to match up to the actual utilisation of the shop. As the median processing time for each facility (sub-operation) was known from the data collection (Chapter 6), Table 7.3, the processing times from each of the sub-operations were made equal to the median operation processing times, Table 7.4.

Facility (sub-operation)	Median processing time (min)	Median processing time (no. of shifts)
F5	960 min	2 shifts
F1	960 min	2 shifts
F2	960 min	2 shifts
T1	480 min	1 shift
T2	480 min	1 shift
S1	960 min	2 shifts
S2	960 min	2 shifts
O1	4800 min	10 shifts
O2	4800 min	10 shifts
C	1920 min	4 shifts
P	2880 min	6 shifts
I	4320 min	9 shifts
F8	960 min	2 shifts
R1	1920 min	4 shifts
R2	1920 min	4 shifts
R3	1920 min	4 shifts
L	960 min	2 shifts

Table 7.3: Median processing times for all facilities.

Operation (O)	Sub-operation (SO)	Total operation processing time
α	F5 + (F1 or F2) + (T1 or T2) = **3 SO**	**2400 min**
β	(S1 or S2) = **1 SO**	**960 min**
γ	(O1 or O2) + F8 = **2 SO**	**4800 min**
δ	C = **1 SO**	**1920 min**
ε	P = **1 SO**	**2880 min**
ζ	I = **1 SO**	**4320 min**
η	F8 + (R1 or R2 or R3) + L= **3 SO**	**3840 min**
θ	F5 + (F1 or F2) = **2 SO**	**1920 min**
ι	(O1 or O2) = **1 SO**	**3840 min**
κ	L = **1 SO**	**960 min**

Table 7.4: Operations, sub-operations and total operation processing times for all facilities.

Figure 7.2 through to Figure 7.11 schematically shows the product routing for each operation for Model 42a and Model 42b. Each sub-product family is a combination of one or more of those operations.

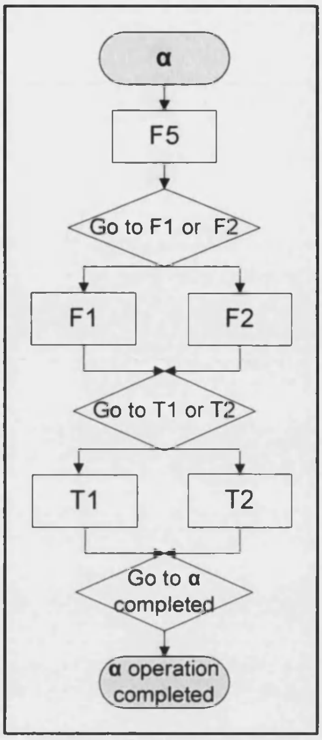


Figure 7.2: Operation α.

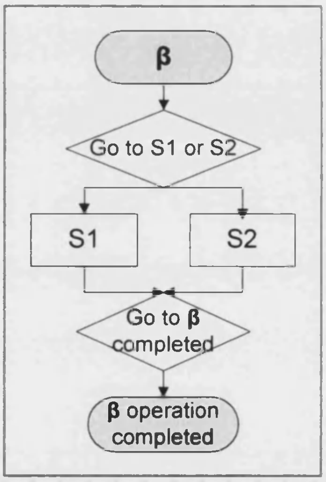


Figure 7.3: Operation β.

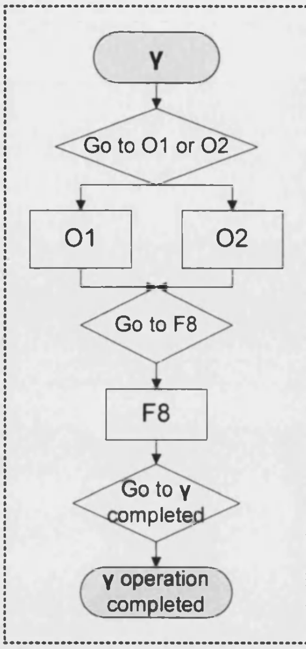


Figure 7.4: Operation γ.

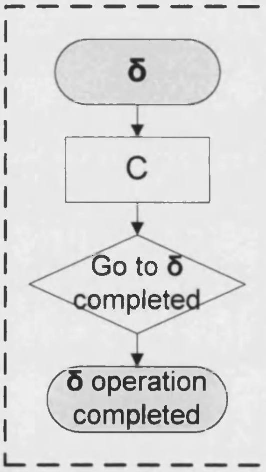


Figure 7.5: Operation δ.

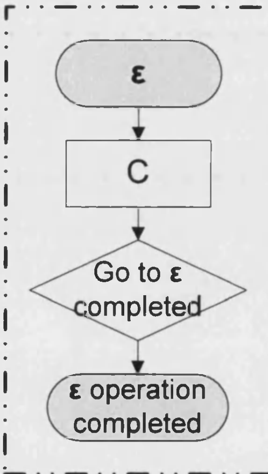


Figure 7.6: Operation ε.

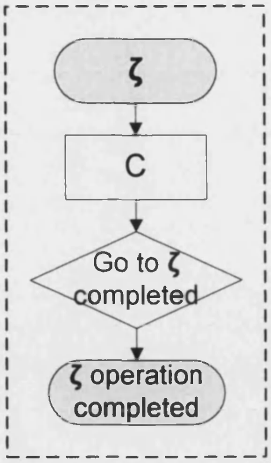


Figure 7.7: Operation ζ.

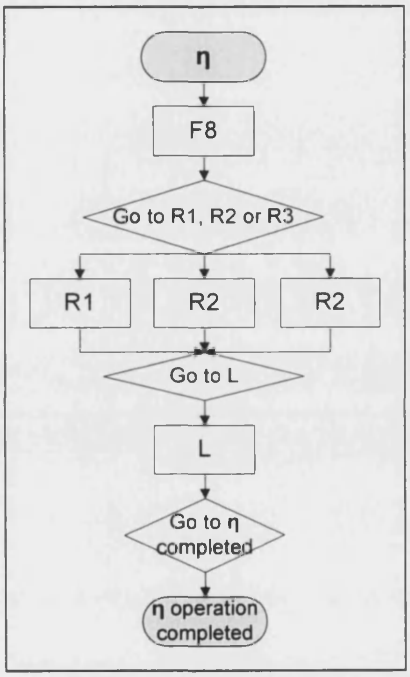


Figure 7.8: Operation η.

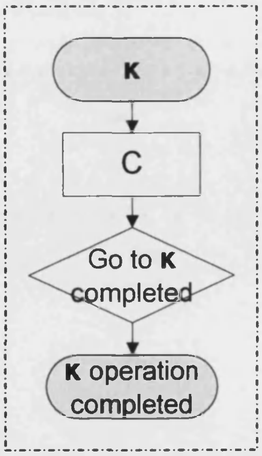


Figure 7.9: Operation κ.

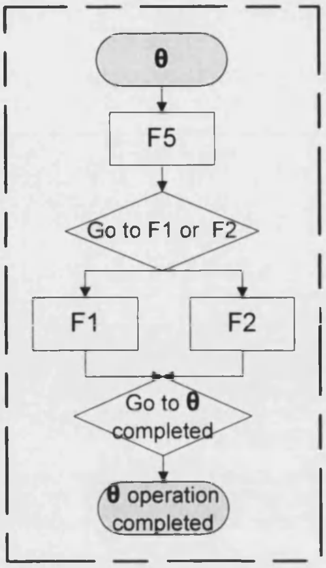


Figure 7.10: Operation θ.

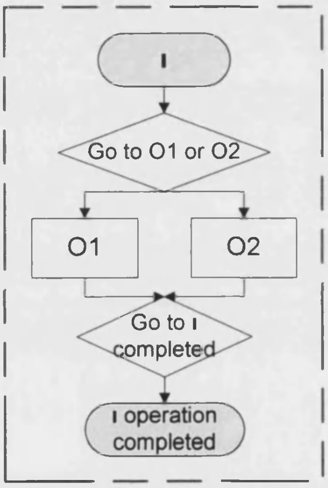


Figure 7.11: Operation ι.

Table 7.5 shows the operations (routing) that each sub-product family go through. Furthermore, Table 7.5 displays the total median processing time for each sub-product family in minutes and days (shifts). In order to estimated due dates of jobs, it was also necessary to include non-working time. Hence, a column where extra time for weekends, where no work takes place, was included. The actual processing time and the weekend free time are thereafter summaries and the total time is calculated. For example A51 (Row 1, Table 7.5) time spent in the shop (processing time + off-shift time) would be:

"(27 days processing time + 10 days extra weekend time) x 24 hours x 60 minutes = 53280 minutes"

Product family	Sub-product family	Operations for sub-product families	Total median processing time for each sub-product family (minutes)	Tot processing time for sub-product families (1 day=1 shift)	Extra time for weekend	Total days	Total minutes
A	A51	αβγδε	(2400+960+4800+1920+2880) = 12960	27 days	10 days	37	53280
A	A41	αβδε	(2400+960+1920+2880) = 8160	17 days	6 days	23	33120
A	A42	αβγζ	(2400+960+4800+4320) = 12480	26 days	10 days	36	51840
A	A43	αηδε	(2400+3840+1920+2880) = 11040	23 days	8 days	31	44640
A	A44	αβηζ	(2400+960+3840+4320) = 11520	24 days	8 days	32	46080
A	A31	αβδ	(2400+960+1920) = 5280	11 days	4 days	15	21600
A	A32	αβζ	(2400+960+4320) = 7680	16 days	6 days	22	31680
A	A33	αηζ	(2400+3840+4320) = 10560	22 days	8 days	30	43200
A	A34	αβη	(2400+960+3840) = 7200	15 days	4 days	19	27360
A	A21	αβ	(2400+960) = 3360	7 days	2 days	9	12960
A	A22	αγ	(2400+4800) = 7200	15 days	4 days	19	27360
A	A23	αη	(2400+3840) = 6240	13 days	4 days	17	24480
A	A24	αζ	(2400+4320) = 6720	14 days	4 days	18	25920
A	A11	α	2400	5 days	0 days	5	7200
A	A12	β	960	2 days	0 days	2	2880
A	A13	ε	2880	6 day	2 days	8	11520
A	A14	δ	1920	4 day	0 days	4	5760
A	A15	η	3840	8 days	2 days	10	14400
B	B51	αβγδε	(2400+960+4800+1920+2880) = 12960	27 days	10 days	37	53280
B	B41	αβγε	(2400+960+4800+2880) = 11040	23 days	8 days	31	44640
B	B31	αβδ	(2400+960+1920) = 5280	11 days	4 days	15	21600
B	B32	αηβ	(2400+3840+960) = 7200	15 days	4 days	19	27360
B	B21	αβ	(2400+960) = 3360	7 days	2 days	9	12960
B	B22	αη	(2400+3840) = 6240	13 days	4 days	17	24480
B	B23	θη	(1920+3840) = 5760	12 days	4 days	16	23040
B	B24	θκ	(1920+960) = 2880	6 days	2 days	8	11520
B	B25	θβ	(1920+960) = 2880	6 days	2 days	8	11520
B	B11	α	2400	5 days	0 days	5	7200
C	C31	κβη	(1920+960+3840) = 6720	14 days	4 days	18	25920
C	C21	αβ	(2400+960) = 3360	7 days	2 days	9	12960
C	C22	αη	(2400+3840) = 6240	13 days	4 days	17	24480
C	C23	θη	(1920+3840) = 5760	12 days	4 days	16	23040
C	C24	θκ	(1920+960) = 2880	6 days	2 days	8	11520
C	C25	θβ	(1920+960) = 2880	6 days	2 days	8	11520
C	C26	θη	(1920+3840) = 5760	12 day	4 days	16	23040
C	C11	β	960	2 days	0 days	2	2880
C	C12	α	2400	5 days	0 days	5	7200
D	D51	αβιζε	(2400+960+3840+4320+2880) = 14400	30 days	10 days	40	57600
D	D41	αηβε	(2400+3840+960+2880) = 10080	21 days	8 days	29	41760
D	D42	αιηβ	(2400+3840+3840+960) = 11040	23 day	8 days	31	44640
D	D43	αηδβ	(2400+3840+1920+960) = 9120	19 day	6 days	25	36000
D	D31	αβη	(2400+960+3840) = 7200	15 days	4 days	19	27360

Table 7.5: Operations, sub-operations and total operation processing time for all facilities.

7.4.3 Job generation, job routing and choice of facilities

Job generation

The job generation frequency for Model 18 is based on the data collection of the MC product mix. The frequency of jobs from each of the 18 sub-product families are displayed in Table 7.6. The generation of jobs is modelled according to an integer uniform distribution, which is also displayed in Table 7.6. In Model 42a and Model 42b where another 24 sub-product families have been added, jobs needed to be generated to a different pattern, Table 7.7. At TC about 50% of the jobs comes from customer MC. The model reflects this by generating 49% of the jobs from the MC product families, with the same frequency as for Model 18. The new sub-products added to Model 42a and 42b share the other 51% of the jobs. For this 51% the sub-families have been given arrival frequencies so as to increase utilisation, e.g. jobs that go through several facilities will in general be generated more frequently. This was established through a trial and error approach, where a range of different job generation frequencies were tested during the model building.

Job routing

Each sub-product family has a specific routing through the job shop. The Witness "integer attribute" named "ICON" was used to differentiate between sub-product families and job routes. Each sub-product family is given an ICON attribute. The ICONs were also modelled using different colours for each sub-product family, which made it easier to verify that the products took the correct route through the shop. When a job has finished its processing at a facility the job is pushed from the facility (using the "To" function on the Witness code for machine codes) to the buffer and then to the next facility on the route. The next facility will then pull jobs from its buffer. When jobs finish their last processing on the final facility of their route, they are pushed to the "Statistics" machine. This machine or facility contains equations to calculate if jobs are late or early and how late or early they are. This is also summarised depending on product families and sub-product families. This data is used to assess the performance of the changeover sensitive heuristics.

Product family	Sub-product family	Frequ-ency (%)	Integer uniform distribution number
1	A51	8%	x>=1ANDx<=8
2	A41	11%	x>=9ANDx<=19
2	A42	6%	x>=20ANDx<=25
2	A43	3%	x>=26ANDx<=28
2	A44	3%	x>=29ANDx<=31
3	A31	14%	x>=32ANDx<=45
3	A32	8%	x>=46ANDx<=53
3	A33	3%	x>=54ANDx<=56
3	A34	3%	x>=57ANDx<=59
4	A21	8%	x>=60ANDx<=67
4	A22	8%	x>=68ANDx<=75
4	A23	8%	x>=76ANDx<=83
4	A24	3%	x>=84ANDx<=86
5	A11	3%	x>=87ANDx<=89
5	A12	3%	x>=90ANDx<= 92
5	A13	3%	x>=93ANDx<= 95
5	A14	3%	x>=96ANDx<=98
5	A15	2%	x>=99AN x<=100

Table 7.6: Job generation frequency for Model 18.

Product family	Sub-product family	Frequ-ency (%)	Integer uniform distribution number
A	A51	4%	x>=1ANDx<=4
A	A41	5%	x>=5ANDx<=9
A	A42	3%	x>=10ANDx<=12
A	A43	2%	x>=13ANDx<=14
A	A44	2%	x>=15ANDx<=16
A	A31	6%	x>=17ANDx<=22
A	A32	4%	x>=23ANDx<=26
A	A33	2%	x>=27ANDx<=28
A	A34	2%	x>=29ANDx<=30
A	A21	3%	x>=31ANDx<=33
A	A22	4%	x>=34ANDx<=37
A	A23	3%	x>=38ANDx<=40
A	A24	2%	x>=41ANDx<=42
A	A11	1%	x>=43ANDx<=43
A	A12	2%	x>=44ANDx<=45
A	A13	1%	x>=46ANDx<=46
A	A14	2%	x>=47ANDx<=48
A	A15	1%	x>=49ANDx<=49
B	B51	2%	x>=50ANDx<=51
B	B41	1%	x>=52ANDx<=52
B	B31	2%	x>=53ANDx<=54
B	B32	2%	x>=55ANDx<=56
B	B21	2%	x>=57ANDx<=58
B	B22	1%	x>=59ANDx<=59
B	B23	1%	x>=60ANDx<=60
B	B24	2%	x>=61ANDx<=62
B	B25	3%	x>=63ANDx<=65
B	B11	1%	x>=66ANDx<=66
C	C31	1%	x>=67ANDx<=67
C	C21	1%	x>=68ANDx<=68
C	C22	1%	x>=69ANDx<=69
C	C23	1%	x>=70ANDx<=70
C	C24	2%	x>=71ANDx<=72
C	C25	5%	x>=73ANDx<=77
C	C26	1%	x>=78ANDx<=78
C	C11	1%	x>=79ANDx<=79
C	C12	1%	x>=80ANDx<=80
D	D51	4%	x>=81ANDx<=84
D	D41	4%	x>=85ANDx<=88
D	D42	5%	x>=89ANDx<=93
D	D43	4%	x>=94ANDx<=97
D	D31	3%	x>=98ANDx<=100

Table 7.7: Job generation frequency for Model 42a and 42b.

Choice of facilities

Throughout the job shop there are several operations that have parallel facilities. Say for instance that three facilities (R1, R2 and R3) share a buffer were all jobs go through before entering one of the facilities. The facilities would in this case fill up from R1 to R3 and ultimately facility R1 would gain a higher utilisation as this would always be the first choice. This would not reflect the utilisation of facilities accurately, considering the real utilisation (Chapter 6). Therefore, the percentage rule in Witness was applied to parallel facilities, such that it reflected the different utilisations. The procedure for this is detailed below for each parallel facility.

Facility T1 and Facility T2

Actual utilisations	**Split for Witness % rule**
T1 = 61% utilisation	T1 % = 61% / 107% = 57%
T2 = 46% utilisation	T2 % = 46% / 107% = 43%
Total: 107% ≠ (53.5% each)	**Total: 57% + 43% = 100%**

Therefore, in the joint buffer for T1 and T2, 57% of the jobs are directed to T1 and 43% of jobs are directed to T2.

Facility R1, Facility R2 and Facility R3

Actual utilisations	**Split for Witness % rule**
R1 = 51% utilisation	R1 % = 51% / 150% = 34%
R2 = 60% utilisation	R2 % = 60% / 150% = 40%
R3 = 39% utilisation	R3 % = 39% / 150% = 26%
Total: 150% ≠ (50% each)	**Total: 34% + 40% + 26% = 100%**

Therefore, in the joint buffer for R1, R2 and R3, 34% of the jobs are directed to R1, 40% of the jobs are directed to R2 and 26% of jobs are directed to R3.

Parallel facilities used 50%

Facility F1 (50%) and Facility F2 (50%)

Facility S1 (50%) and Facility S2 (50%)

Facility O1 (50%) and Facility O2 (50%)

7.4.4 Modelling of job dispatching heuristics

After jobs have been generated (section 7.4.3) they are all sent to a "Schedulingbuffer" and a "HelpMachine". It is in those two elements the different sequencing scheduling rule heuristics are modelled. Some of the heuristics do not require extensive programming. For instance, the First Come First Served rule, FCFS is modelled by the "HelpMachine" choosing the first job in the queue of waiting jobs in the "Schedulingbuffer". FCFS picks any job and it does not consider what product family or sub-product family this job is from. For other "simple" sequencing rules, the programming could be incorporated in the "Schedulingbuffer". However, other more complex rules, e.g. a rule that sequence the jobs by placing all jobs from the same product families in sequence required a lot more programming. Such rules were programmed by creating a separate function was then called in the "Input Rule" of the "HelpMachine". It was also necessary to incorporate equations that counted the number of jobs from each sub-product and product family that went through the "HelpMachine". This was included in the "Actions on Output" on the "HelpMachine". The operations of all heuristics tested are discussed in detail in the experimentation design sections of (Chapter 8, 9 and 10). Figure 7.12 shows a snapshot of the simulation model of the "Schedulingbuffer" and the "HelpMachine".

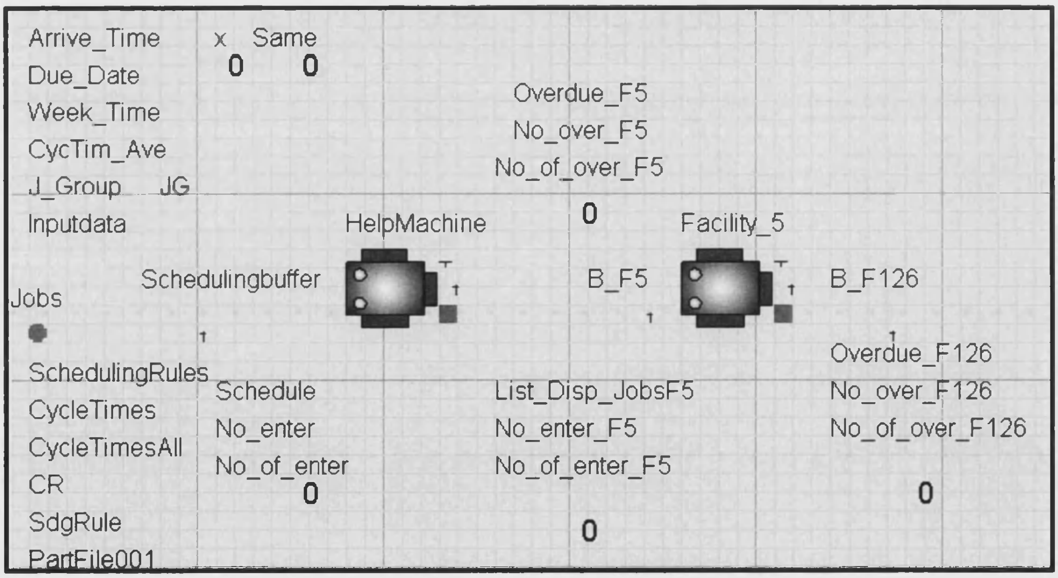


Figure 7.12: Snapshot of "Schedulingbuffer" and "HelpMachine".

7.5 VALIDATION OF UTILISATION AND THROUGHPUT

In order to validate the simulation model against the real system, utilisation levels for the facilities and the total throughput of the model were investigated. When performing validation the models were run for ten years and replicated ten times with different random number settings. This resulted in a total of *100 years* of running time of the validation models.

When performing experimentation certain parameters such as "inter-arrival time of jobs (horizon)" and "queue discipline" were varied to perform experimentation under different conditions and scheduling scenarios. However, all three validation models were run under the same conditions. The original settings reflect the actual situation at TC and the validation models were also applied as the benchmark when experiments were run. Table 7.8, Table 7.9 and Table 7.10 summarise the parameters for the benchmark Models 18, 42a and 42b respectively.

Model 18	
No. of facilities	**17**
No. of product families	**5**
No. of sub-product families	**18**
Inter-arrival time of jobs (horizon)	**Every 4 weeks**
No. of jobs per inter-arrival time	**15**
Processing times	**1/1**
No. of operations	**7**
Queue discipline	**FCFS**

Table 7.8: Validation parameters for Model 18.

Model 42a	
No. of facilities	**17**
No. of product families	**4**
No. of sub-product families	**42**
Inter-arrival time of jobs (horizon)	**Every 4 weeks**
No. of jobs per inter-arrival time	**16**
Processing times	**1/1**
No. of operations	**9**
Queue discipline	**FCFS**

Table 7.9: Validation parameters for Model 42a.

Model 42b	
No. of facilities	**17**
No. of product families	**4**
No. of sub-product families	**42**
Inter-arrival time of jobs (horizon)	**Every 4 weeks**
No. of jobs per inter-arrival time	**160**
Processing times	**1/10**
No. of operations	**9**
Queue discipline	**FCFS**

Table 7.10: Validation parameters for Model 42b.

In Chapter 6, section 6.3.7 it is stated that Facility five is highly utilised and is run with two shifts a day, seven days a week (960 min working time from Mon – Sun). However, when validating the models the utilisation for Facility five is slightly lower than the desired level. This could possible be for two reasons; first it has been assumed when calculating the utilisation from the schedule the weekend shift always takes place in Facility five and secondly the reason might be that a different area of TC businesses occasionally uses Facility five as well. This has been solved in the models by removing the night shift on weekends. This creates a utilisation that compares very well to the real system.

The model was first validated with jobs using the data subset of products from the Major Customer (MC). This meant that all jobs were generated from the subset of MC products. This was Model 18. This model was particularly difficult to validate. Using a subset of products from MC meant that the utilisation of the shop was imbalanced. The utilisation was first recorded from Model 18 with exactly the same settings as Model 42 (Table 7.9). The result from the utilisation comparison of Model 18 and the real system is shown in Figure 7.13.

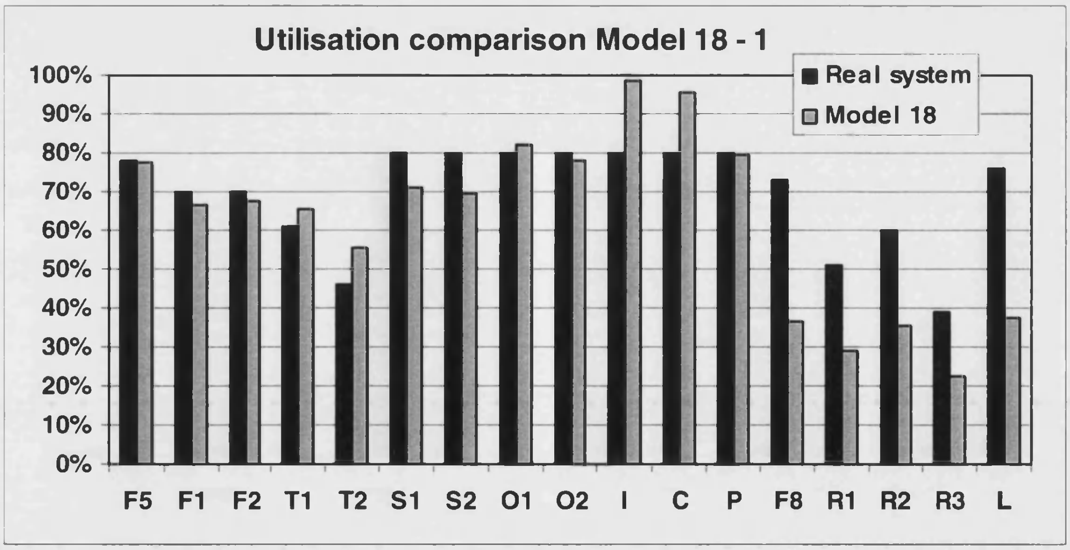


Figure 7.13: Utilisation comparison of data collection and Model 18 - 1.

As can be seen in Figure 7.13, for Facility F5 through to O2 and P the utilisation is similar to the utilisation in the real system. However, facility F8, R1, R2, R3 and L all have lower utilisations, than the real system. This is an indication that purely applying the subset of MC products does not give an accurate utilisation for all facilities throughout the shop. Furthermore, facility I and C gives an utilisation that is too high and in the case of facility I the utilisation is approaching 100% utilisation. The low utilisation does not create a problem when validating the model, but the nearly 100% utilisation does. This creates long queues of jobs in the model and impacts the *mean time in process* and *work-in-progress measures*, so that it is difficult to achieve a stable process. This made validating Model 18 regarding warm-up period and number of replications difficult when the model was run for a long time, especially if the model was ran for over ten years. Model 18 was therefore tested under slightly different conditions to come to terms with this. The processing time for I, was estimated to 4320 min (9 days) and this works very well for Model 42a. However, as the job mix for Model 18 is different from Model 42 a, and a queue is created for I in Model 18, it was decided to reduce the estimated time for I from 4320 min (9 days) to 3360 (7 days) in Model 18. This improves the situation slightly, but it also seems that the imbalance of the job mix for Model 18 cannot cope with a job release frequency of 16 jobs every four weeks. The job release frequency was therefore reduced to 15 jobs every four weeks. The reduction in processing time of I and reducing the number of jobs released stabilised the model and it is validated accordingly. Figure 7.14 shows the utilisation of Model 18 after the changes are incorporated. If the utilisation of each facility in the real system is added to a total number it gives an utilisation of 1184%. Model 18-2 gives an utilisation of totally 1008%. Hence Model 18-2 is 14.9% lower than the real system (((1184%-1008%)/1184%)*100=14.9%). Because the sub-set of products in Model 18 is imbalanced it is difficult to reach total difference in utilisation that is closer to zero.

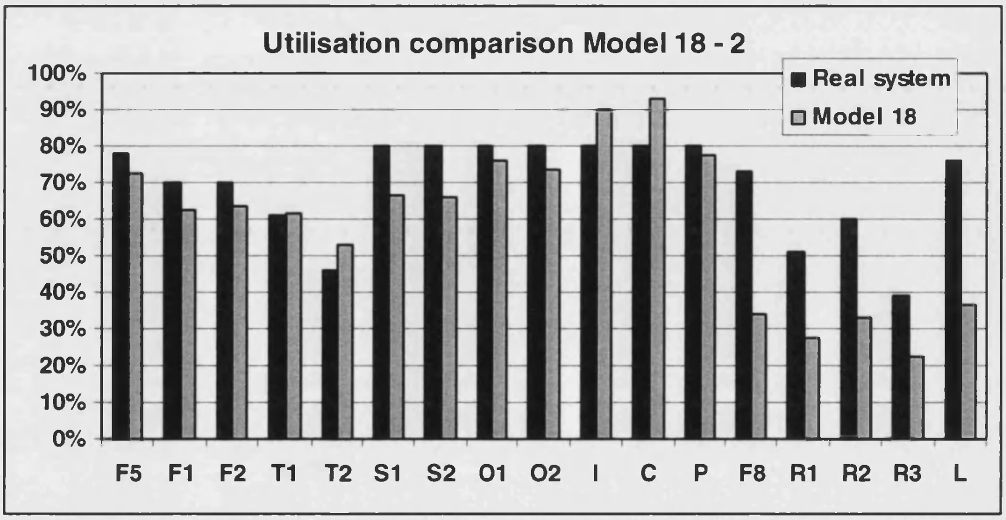


Figure 7.14: Utilisation comparison of data collection and Model 18 - 2.

The utilisation of Facility I has in this comparison been reduced from nearly 100% to 90%. However, the utilisations for facility F8, R1, R2, R3 and L are still too low compared to the real system. In order to come to terms with this the routing pattern of products was modified and Model 42a was created. The utilisation of Model 42a more accurately reflects the real shop. The utilisation of Model 42a compared to the real system is shown in Figure 7.15. This graph shows an utilisation that reflects the real system well. Again the total utilisation in the real system is 1184% and Model 42a creates a total utilisation of 1213%. Hence Model 42a is 2.4% higher than the real system (((1184%-1213%)/1184%)*100=-2.4%). This accuracy is considered adequate.

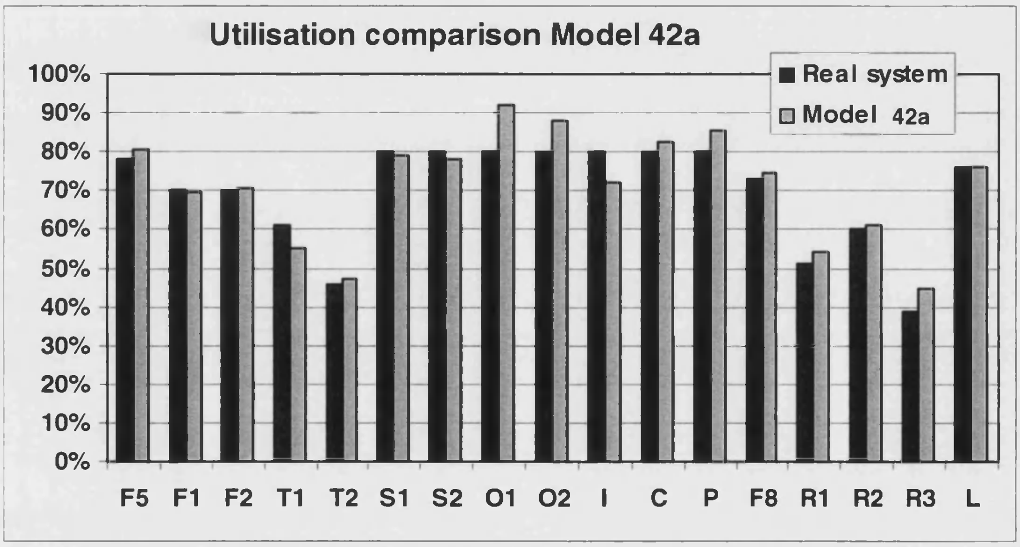


Figure 7.15: Utilisation comparison of data collection and Model 42a.

Model 42b has the same product mix as Model 42a, but the processing times that are 1/10 of the processing times for Model 42a. Figure 7.16 shows the result of the validation of the utilisation for Model 42b. The utilisation is compared to the utilisation of the real system, although Model 42b has been run with 1/10 of the processing times and with 160 jobs released every four weeks instead of 16 jobs, as in Model 42a. The utilisation of Model 42b fits the real utilisation well. Model 42b was also tested with increased number of jobs from 160 jobs released every four weeks to 180 jobs. However, this created very long queues for the facilities O1, O2, C and P. Hence, it was decided to release 160 jobs every four weeks.

The total utilisation in the real system is 1184% and after validation Model 42b reaches a total utilisation of 1240%. Hence Model 42b is 4.7% higher than the real system (((1184%-1240%)/1184%)*100=-4.7%) a difference of 4.7% between the systems. This is considered sufficiently accurate.

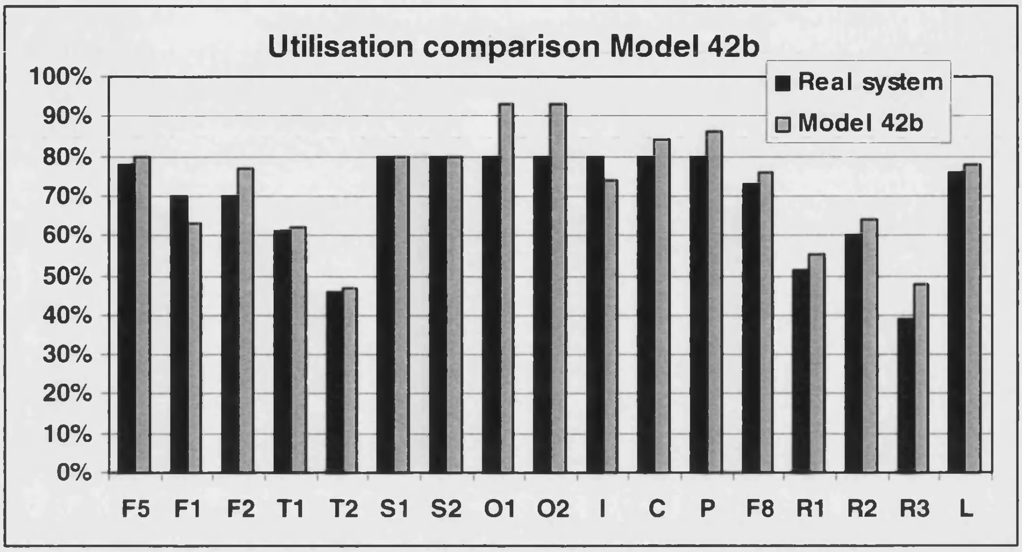


Figure 7.16: Utilisation comparison of data collection and Model 42b.

Table 7.11 displays the throughput of products per year as is expected of the three models compared to the average output when running the models for ten year with ten replications and calculating the average throughput. The result is satisfying for all three Models.

Average/year	Expected	Throughput
Model 18	195	195
Model 42a	208	203
Model 42b	1950	1955

Table 7.11: Throughput of Model 18, Model 42a and Model 42b.

7.6 DETERMINING THE WARM-UP PERIOD AND RUN-LENGTH

Simulation runs can be characterised as *terminating* or *non-terminating*. A natural termination point could be the completion of a production schedule or an empty condition such as when a bank closes at the end of the day. A non-terminating model measures the output when the interest is in investigating the behaviour of the model when operating during a long run. Measurers of interest in a non-termination simulation would for instance be the mean time a product spends in the system or the utilisation of machines.

Since this project essentially investigates scheduling policies it would be possible to apply a terminating model. However, in this research studying traditional scheduling measures, as well as gaining an understanding of the overall process is important. This enables study of parameters such as throughput capability as well as a range of performance measures. For these types of measures a termination model could be used to simulate different scenarios and the results compared. Although measures such as average time in process and utilisation will give slightly lower values as the model will run empty at the end to finish off a list of jobs. To overcome this and to collect data from a realistic scenario where the shop is not run empty a non-termination model was used. This model was selected as it enabled the investigation of all the performance measures of interest, including the measure of late jobs and their percentage.

For non-terminating simulation runs the model often reaches a so called *steady state*. Steady-state occurs after an initial warm-up period. In a steady state the output is varying according to some fixed distribution (Robinson, 2004). For example, when a simulation run starts the model is empty (unless initial conditions have been specified), but eventually fills up until it reaches "normal" average production levels. If the nature of a model is that it needs an initial warm-up period, then measuring the results during this period may give misleading data. For examples utilisation levels of machines may be too high or too low. When using the simulation model and measuring and comparing the output from the model, it is important that the model has reached a so called steady-state.

In this research warm-up period was determined in order to make sure that the warm-up period was accounted for and the steady state of the model was reached.

A common method to determine the warm-up period is the *Welch's Method* (Robinson, 2004 and Law and Kelton, 2000). Welch's method is based on plotting moving averages and the procedure applied for this research was:

- To perform a series of replications of five replications in each series for 21 different time periods with an interval of 12 weeks between each time period.
- To measure output data from all replications (five different measures were taken).
- To calculate the mean of the output data across the replications for each time period.
- To calculate the moving average with a window w (window size used was w = 5).
- To plot the moving averages on a time scale.
- If the data had not been smooth recalculation with increased window size (w) would have taken place.
- The length of the warm-up time was identified where the time series became flat.

The moving averages were calculated according to:

$$\bar{Y}_i(w) = \begin{cases} \dfrac{\sum_{s=-(i-1)}^{i-1} \bar{Y}_{i+s}}{2i-1} & if \quad i = 1,\ldots,w \\ \dfrac{\sum_{s=-w}^{w} \bar{Y}_{i+s}}{2w+1} & if\ i = w+1,\ldots,m-w \end{cases}$$

Where:

$\bar{Y}_i(w)$	=	moving average of window size w
$\bar{Y}_i$	=	time-series of output data (mean of the replications)
i	=	period number
m	=	number of periods in the simulation run

Equation 7.1: Calculation of moving average.

The result of the moving average calculation for the measure, mean time for a job in the system, is displayed in Table 7.12. All other tables of moving average calculations are displayed in Appendix F (please refer to attached CD-ROM). Other measures used to for determining the warm-up period were; average work in progress (WIP) and utilisation of three facilities, Facility 5, 8 and S1. Mean time and utilisation measures are commonly applied to determine the steady state. The three facilities where the utilisation levels were studied belong to three different testing operations. Those three were chosen because F5 has the most number of jobs going through, F8 is also a facility were many jobs will pass and S1 was randomly chosen as a facility from another operation.

Replication number	Number of replications	Run length	Mean time (Days)	Moving Average (w=5)
1	5	120960 min (12 weeks)	25.37	25.37
2	5	241920 min (24 weeks)	32.72	31.89
3	5	362880 min (36 weeks)	37.57	35.63
4	5	483840 min (48 weeks)	40.35	37.97
5	5	604800 min (60 weeks)	42.15	39.62
6	5	725760 min (72 weeks)	43.32	40.83
7	5	846720 min (84 weeks)	44.33	42.77
8	5	967680 min (96 weeks)	45.05	44.09
9	5	1088640 min (108 weeks)	45.76	44.98
10	5	1209600 min (120 weeks)	46.16	45.63
11	5	1330560 min (132 weeks)	46.35	46.14
12	5	1451520 min (144 weeks)	46.73	46.53
13	5	1572480 min (156 weeks)	47.26	46.85
14	5	1693440 min (168 weeks)	47.36	47.15
15	5	1814400 min (180 weeks)	47.45	47.42
16	5	1935360 min (192 weeks)	47.60	47.71
17	5	2056320 min (204 weeks)	47.73	
18	5	2177280 min (216 weeks)	47.90	
19	5	2298240 min (228 weeks)	48.32	
20	5	2419200 min (240 weeks)	48.79	
21	5	2540160 min (252 weeks)	49.27	

Table 7.12: Moving average of mean time (window (w) = 5) for Model 18 and measure "mean time for a job in the system".

Figure 7.17 shows the warm-up plot for Model 18, Figure 7.18 shows the warm-up plot for Model 42a and Figure 7.19 shows the warm-up plot for Model 42b.

All plots, except "mean time", for Model 18 even out after about 150 weeks, with the utilisation measures becoming stable around the 100 weeks point. To ensure the stable state for all measures considered, a warm-up period of three years was selected.

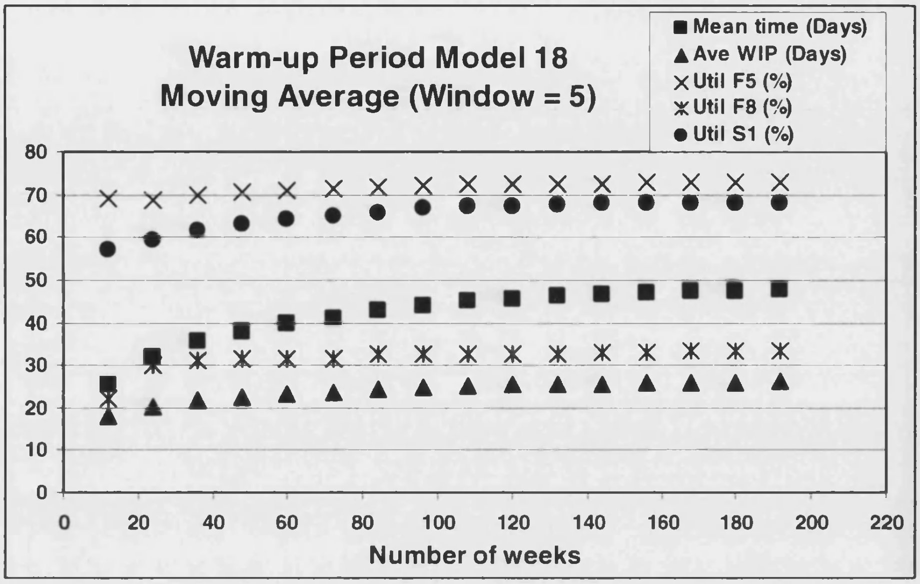


Figure 7.17: Warm-up plot of Model 18.

As for Model 18, utilisation measures for Model 42a even out around 100 weeks, whereas the "WIP" and "mean time" measures need about 150 weeks to reach their steady state. There was a slight increase in the "mean time" after 150 weeks. This was accounted for due to the fact that there are slightly too many jobs going into the shop (it is over capacity). This creates queues in the system increasing the "mean time". It could also reflect the real system, in the sense that if this took place in the real system, some over time would take place to reduce the queues, whereas this is not programmed in the model, hence the "mean time" increases if the model is run over a long time period. Since the increase was not major it was decided to accept this fact and run Model 42a with a warm-up time of three years, 156 weeks. The same warm-up period as Model 18.

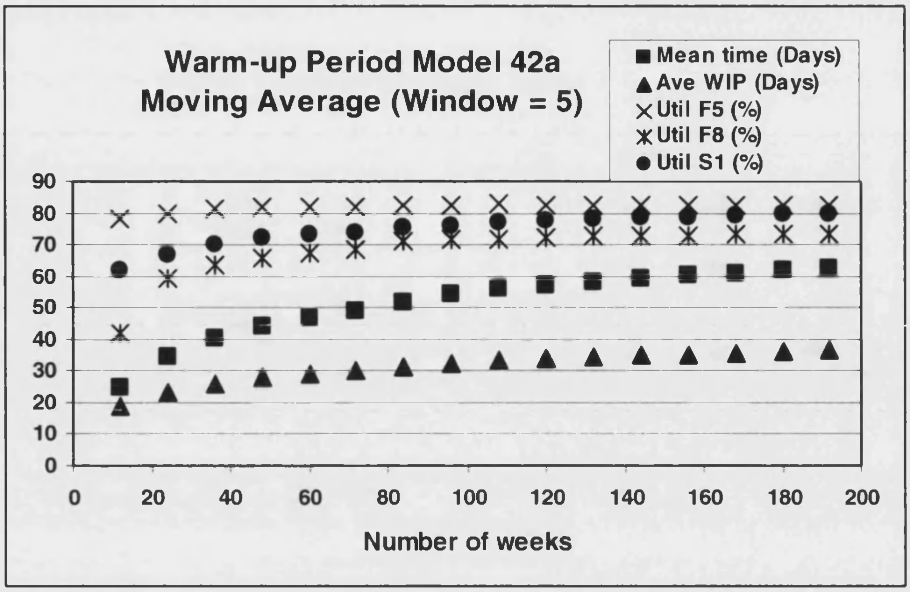


Figure 7.18: Warm-up plot of Model 42a.

For Model 42b (with the shorter processing times) all performance measures evened out after 100 weeks. Model 42b copes well with the number of jobs entered (160 every 4 weeks compared to 16 every four weeks for Model 42a). For Model 42b a warm-up time of two years would be sufficient. However, increasing the warm-up to three year to mirror Model 18 and Model 42b would do no harm, especially since it would not take many more minutes to run. Therefore, a warm-up period of three years (156 weeks) was also chosen for Model 42b.

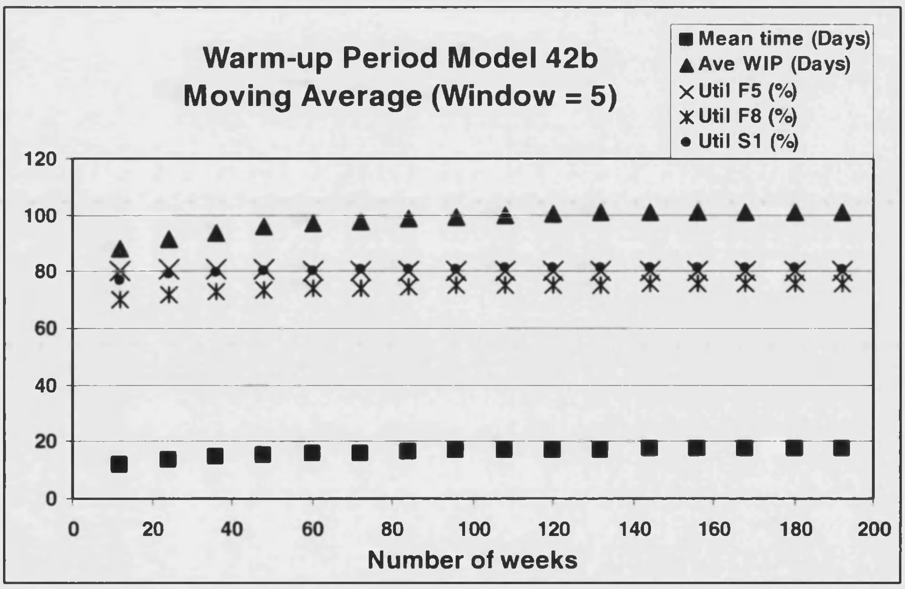


Figure 7.19: Warm-up plot of Model 42b.

Some variables in the Witness software are automatically collected when performing simulation runs, for example utilisation and WIP measures. When a simulation model is run with warm-up periods, the Witness software, reports the values collected after the warm-up period. However, when user defined variables have been created for a model; those variables are not automatically recorded after the warm-up period, but are recorded from the start of warm-up to the end of the total run. The models created for this project all have many user defined variables, such as "number of late jobs". To overcome the issue of the user defined variables not being reset after the warm-up period, an additional part is created in the model. This part enters the model only once at the time 1572480 min (156 weeks or three years). In "Actions on Create" of this part all user defined variables are reset. There are 232 user defined variables in the models.

In summary a warm-up period of three years (156 weeks) was calculated for Model 18 and Model 42a. For Model 42b a warm-up time of about 60 weeks was calculated. However, because consistence in the experimentation was desired, it was decided to apply the three year (156 weeks) run-up time for all three models. All models were then run for a further ten years after the warm-up. Hence, the run-length of each experiment in this research where steady state data was collected was ten years.

7.7 DETERMINING NUMBER OF REPLICATIONS REQUIRED

Once the warm-up time had been ascertained it was also necessary to determine the number of replications required for the simulation experiments in this research. To determine the number of replications for each experiment, cumulative means were calculated for five performance measures;

- Mean time
- WIP
- Utilisation for F5
- Utilisation for F8
- Utilisation for S1.

All three models were run for ten years, plus an additional warm-up time of three years was included, adding up to a total of thirteen years per run. Measures from 20 replications for each model were recorded. Each of the 20 replications was run with different random number streams. However, the random number streams were the same for each of the three models.

The "confidence interval method" (Robinson, 2003 pp. 154-156) was applied. First the cumulative mean was calculated and thereafter the standard deviation according to;

$$S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$

Where:

S	=	Standard deviation
X_i	=	the result from replication i
$\overline{X}$	=	mean of the output data from the replications
n	=	number of replications

Equation 7.2: Calculation of standard deviation.

The confidence interval is calculated as;

$$CI = \overline{X} \pm t_{n-1,\alpha/2} \frac{S}{\sqrt{n}}$$

Equation 7.3: Calculation of confidence interval.

CI	=	Confidence Interval
$\overline{X}$	=	mean of the output data from the replications
$t_{n-1,\alpha/2}$	=	Value from Student's t-distribution with n-1 degree of freedom and a significant level of α/2
S	=	Standard deviation of the output data from the replications
n	=	number of replications

A confidence interval of 95% was desired, meaning that a significant level (α) of 5% was chosen. This gives 95% probability that the value of the true mean lies within the confidence interval. The values for Student's *t*-distribution were given in Robinson (2003 p. 303). Because the confidence interval gives an upper and lower limit the significance level is divided by two (α/2) and hence the values at 2.5% significance are chosen. The approach of calculating confidence interval with Student's *t*-distribution is a standard approach described by for example Robinson (2003) and Law and Kelton (2000).

Table 7.13 shows the confidence interval values from replications of measured mean time for Model 42a. All confidence interval tables for the five performance measures and the three models are displayed in Appendix G (please refer to attached CD-ROM).

Replication	Mean time (Days)	Cumulative mean	Standard deviation	Lower interval	Upper interval	Deviation	% Deviation
1	78.40	78.40	n/a	n/a	n/a	n/a	n/a
2	78.63	78.52	0.1626	77.0538	79.9762	0.0186	1.8611
3	77.14	78.06	0.8021	76.0640	80.0493	0.0255	2.5528
4	79.45	78.41	0.9562	76.8835	79.9265	0.0194	1.9406
5	77.95	78.31	0.8527	77.2552	79.3728	0.0135	1.3520
6	76.70	78.05	1.0079	76.9873	79.1027	0.0136	1.3553
7	82.61	78.70	1.9554	76.8887	80.5056	0.0230	2.2980
8	78.56	78.68	1.8110	77.1660	80.1940	0.0192	1.9243
9	77.94	78.60	1.7119	77.2819	79.9137	0.0167	1.6742
10	80.02	78.74	1.6755	77.5414	79.9386	0.0152	1.5222
11	88.82	79.66	3.4298	77.3522	81.9605	0.0289	2.8926
12	91.56	80.65	4.7436	77.6343	83.6623	0.0374	3.7372
13	95.17	81.77	6.0703	78.0972	85.4218	0.0449	4.4719
14	79.04	81.57	5.8775	78.1771	84.9643	0.0416	4.1603
15	73.58	81.04	6.0277	77.6999	84.3761	0.0412	4.1191
16	73.76	80.58	6.1010	77.3321	83.8342	0.0403	4.0344
17	76.42	80.34	5.9929	77.2570	83.4195	0.0384	3.8354
18	89.01	80.82	6.1628	77.7553	83.8847	0.0379	3.7920
19	80.50	80.80	5.9896	77.9163	83.6900	0.0357	3.5727
20	76.62	80.59	5.9044	77.8307	83.3573	0.0343	3.4287

Table 7.13: Confidence interval method: Results from 20 replications (mean time) Model 42a.

The confidence intervals are plotted in Figure 7.21 through to Figure 7.35. Figure 7.20 shows the key to the confidence interval graphs.

Robinson (2003 p. 152) recommends that as a general rule at least three to five replications should be performed. Analysis of Figures 7.21 to 7.25, which show the confidence interval for Model 18, Model 18 needs twelve replications in order for all five measures to reach a confidence interval of 5 %. However, for the three utilisations measures alone, only six replications are needed. The measures that need twelve replications are mean time in system and WIP. It was discussed in section 7.5 that it was difficult to reach a steady state of Model 18. Due to this it was decided to run *Model 18* with *twelve replications*. On the other hand both Model 42a and Model 42b reach a confidence interval of 95% on all measures after five replications. Hence, *Model 42a and Model 42b* were run with *five replications*.

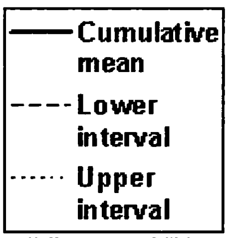
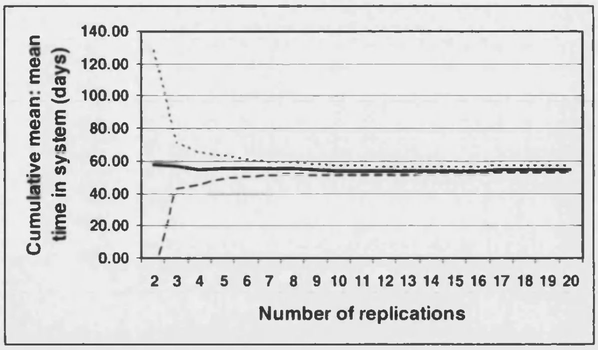
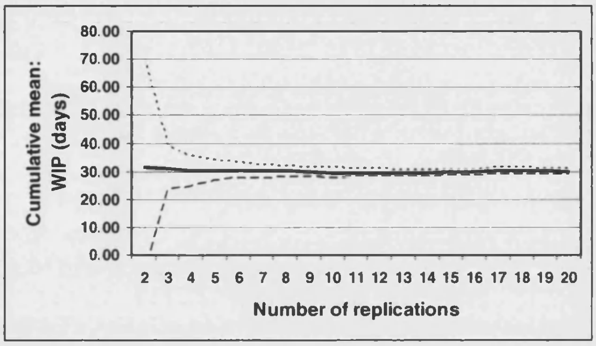


Figure 7.20: Key to all figures of "Number of replications".

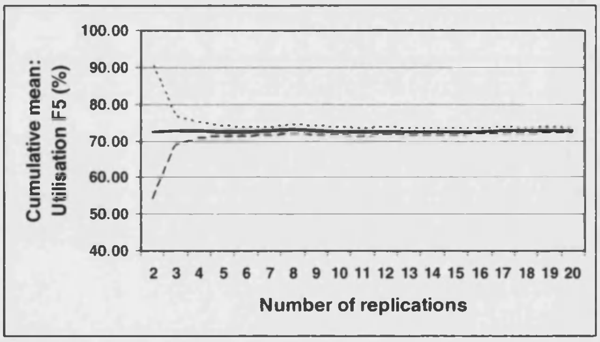
Model 18
Figure 7.21: Plot of cumulative mean and 95% confidence intervals (mean time in system).



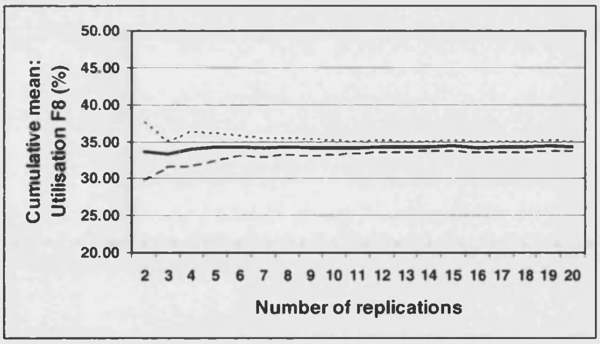
Model 18
Figure 7.22: Plot of cumulative mean and 95% confidence intervals (WIP).



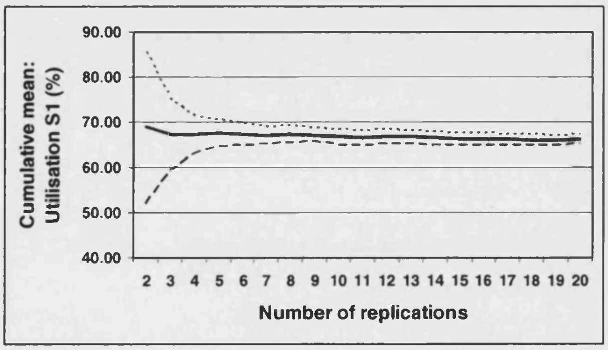
Model 18
Figure 7.23: Plot of cumulative mean and 95% confidence intervals (Utilisation F5).



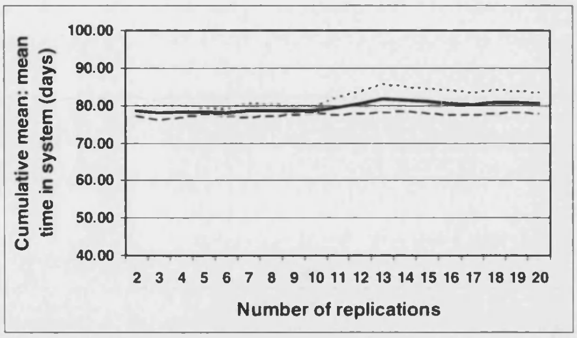
Model 18
Figure 7.24: Plot of cumulative mean and 95% confidence intervals (Utilisation F8).



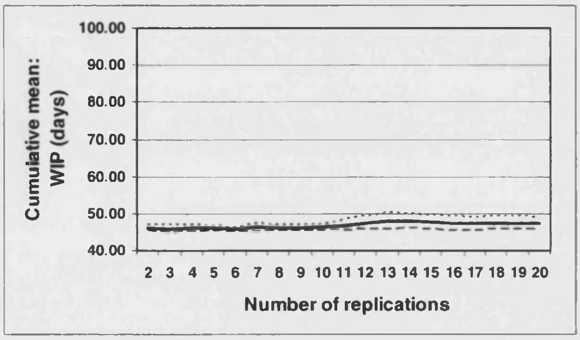
Model 18
Figure 7.25: Plot of cumulative mean and 95% confidence intervals (Utilisation S1).



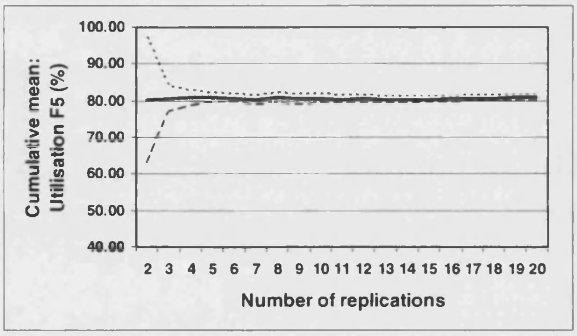
Model 42a
Figure 7.26: Plot of cumulative mean and 95% confidence intervals (mean time in system).



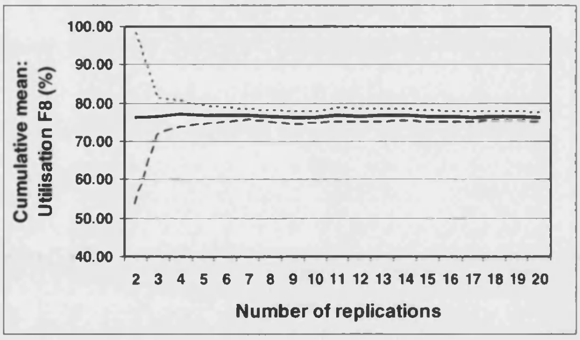
Model 42a
Figure 7.27: Plot of cumulative mean and 95% confidence intervals (WIP).



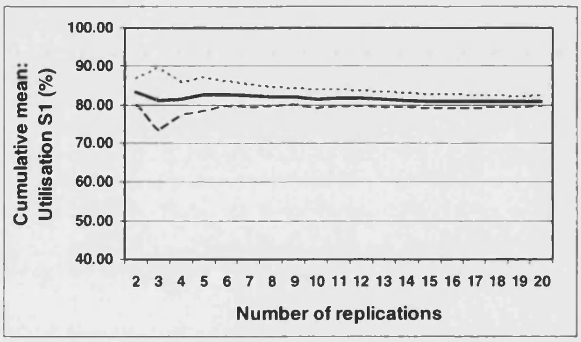
Model 42a
Figure 7.28: Plot of cumulative mean and 95% confidence intervals (Utilisation F5).



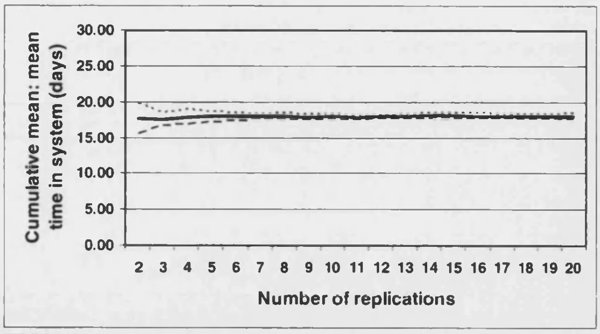
Model 42a
Figure 7.29: Plot of cumulative mean and 95% confidence intervals (Utilisation F8).



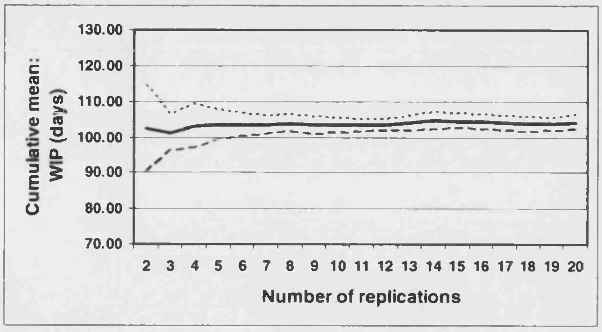
Model 42a
Figure 7.30: Plot of cumulative mean and 95% confidence intervals (Utilisation S1).



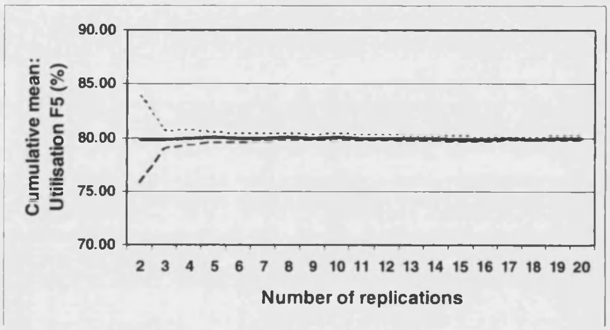
Model 42b
Figure 7.31: Plot of cumulative mean and 95% confidence intervals (mean time in system).



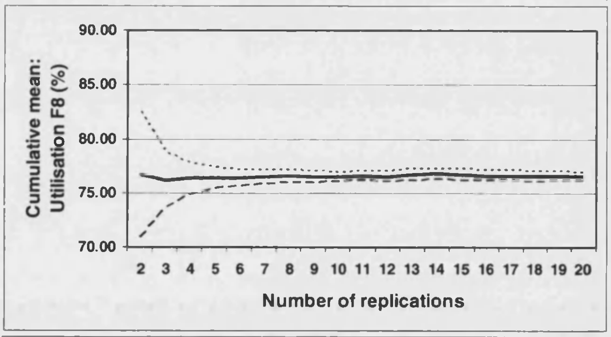
Model 42b
Figure 7.32: Plot of cumulative mean and 95% confidence intervals (WIP).



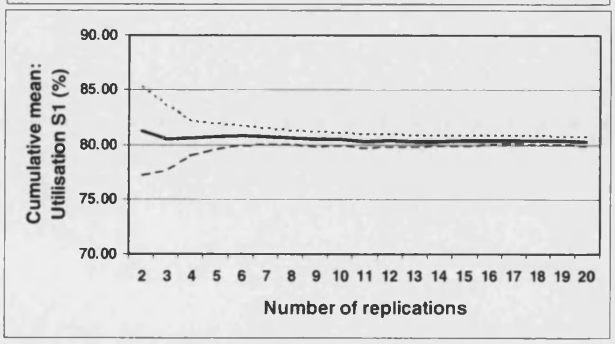
Model 42b
Figure 7.33: Plot of cumulative mean and 95% confidence intervals (Utilisation F5).



Model 42b
Figure 7.34: Plot of cumulative mean and 95% confidence intervals (Utilisation F8).



Model 42b
Figure 7.35: Plot of cumulative mean and 95% confidence intervals (Utilisation S1).



7.8 SENSITIVITY ANALYSIS OF DUE DATE SETTING

To ensure the simulation models provided data to enable the analysis of the effect of different heuristics on changeover reduction it was necessary to undertake sensitivity analysis of key parameters, in this case for due date setting. When determining which model factors that have a significant impact on performance measures sensitivity analysis is an important technique. It was realised that all three models were very sensitive to due date setting. Due date setting was important as this determines the criteria for performance measures such as number of late jobs and how late or early jobs are. However, the due date setting does not affect the actual throughput of products in the model or the time the products spend in the model. This means that being consistent in due date setting, so that the results can be compared, is more important than the actual due date setting.

To investigate and decide on due date setting sensitivity analysis was performed. The three models were run with three different setting of due dates.
In the models due dates are created according to:

"Due Date = IUNIFORM ((Arrival Time + Processing Time Ave) *between* (Arrival Time + Processing Time Ave + Week Time * **Sensitivity Factor**), (Random number stream))"

Where:

IUNIFORM	=	an integer uniform distribution
Arrive Time	=	the arrival time of job to the shop
Processing Time Average	=	the processing time average is calculated from adding up all the median processing times for each sub-product family
Week Time	=	10080 min, which is a 7 day week, with 24 hours per day
Sensitivity Factor	=	this factor has three different levels, 6, 8 and 10, which means an addition of 6, 8 or 10 weeks (Table 7.14).

It may seem long to add 6 to 10 weeks, but as the longest jobs in the shop need 40 days to go through (8 working weeks) this matches the range of jobs. Refer to Table 7.5 for details about median processing times.

Input	Model 18	Model 42a	Model 42b
Input 1	Week time * 6	Week time * 6	Week time * 6
Input 2	Week time * 8	Week time * 8	Week time * 8
Input 3	Week time * 10	Week time * 10	Week time * 10

Table 7.14: Due date setting factors.

Figure 7.36 shows the results from the different due date settings. Model 18 and Model 42a show a high percentage of late jobs, whereas Model 42b has a lower percentage of late jobs. This is probably due to the fact that jobs in Model 42b are shorter (but there are ten times more of them) and many short jobs may go through the shop faster that a few long jobs. To reach a common due date setting for all models it was decided to use the middle factor, which was *eight weeks*.

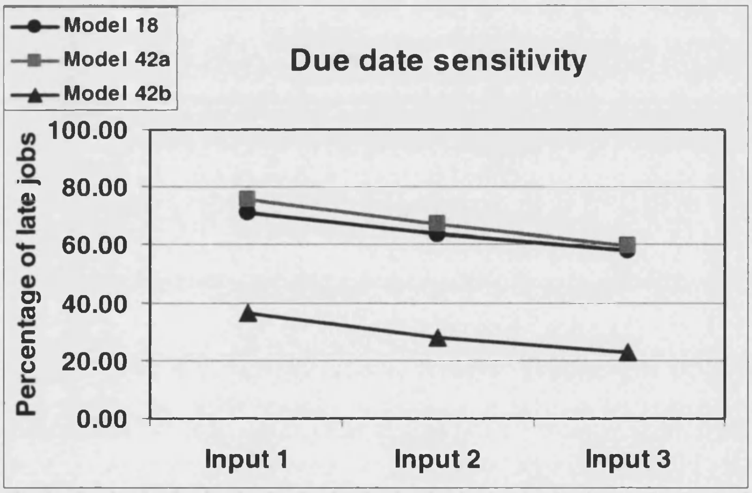


Figure 7.36: Plot of due date sensitivity.

7.9 OTHER EXPERIMENTAL CONDITIONS

Arrival rate of jobs

Jobs arrive in batches every four weeks. The jobs in each batch are sequenced among the batch according to the heuristic currently under investigation. The reason for this choice of arrival rate and job sequencing is to replicate the real industrial setting, as the case study company has a four weeks planning horizon and scheduling of arriving jobs. Jobs are generated according to a uniform distribution, with a percentage frequency (Table 7.6 and 7.7).

Bottlenecked shop

The job shop investigated has one facility that can be described as the bottleneck, as most jobs needs to go through this facility. This is facility F5, which is also the first facility, for many jobs in the shop. However, due to the need for most jobs to visit F5, the F5 facility is the only facility in the shop where two shifts are required, which naturally reduces its impact as a bottleneck.

Non-balanced shop

Another characteristic, of the job shop that has been studied, is the fact that the shop is not balanced. This reflects the utilisation levels of the facilities in the real industrial environment that has been modelled. It is interesting to study an imbalanced shop as much of the previous research of scheduling heuristics have considered balanced shops. However, the different utilisation levels throughout the shop made it difficult to validate the models, especially Model 18. To overcome this Model 18 had a larger number of runs then Models 42a and b.

7.10 SUMMARY OF MODEL BUILDING, VALIDATION, VERIFICATION, WARM-UP PERIOD, RUN-LENGTH AND NUMBER OF REPLICATIONS

Three main models were built and validated. The models were named Model 18, Model 42a and Model 42b after the number of sub-families included in each model.

Verification took place throughout the model building in collaboration with supervisors of the project and experts at the case study company.

Extensive validation procedures took place for each of the three models and resulted in the inclusion of a warm-up period of 156 weeks (three years) for all three models and a run-length of ten years. This means that each experiment ran for a total of thirteen years, taking around ten to twenty minutes in real time to run.

The number of replications needed to give a confidence interval of 95% was concluded to twelve replications for Model 18 and five replications for Model 42a and Model 42b respectively. Overall validation of the models was performed against utilisation of facilities and throughput of jobs.

Figure 7.37, displays the layout of the Witness model.

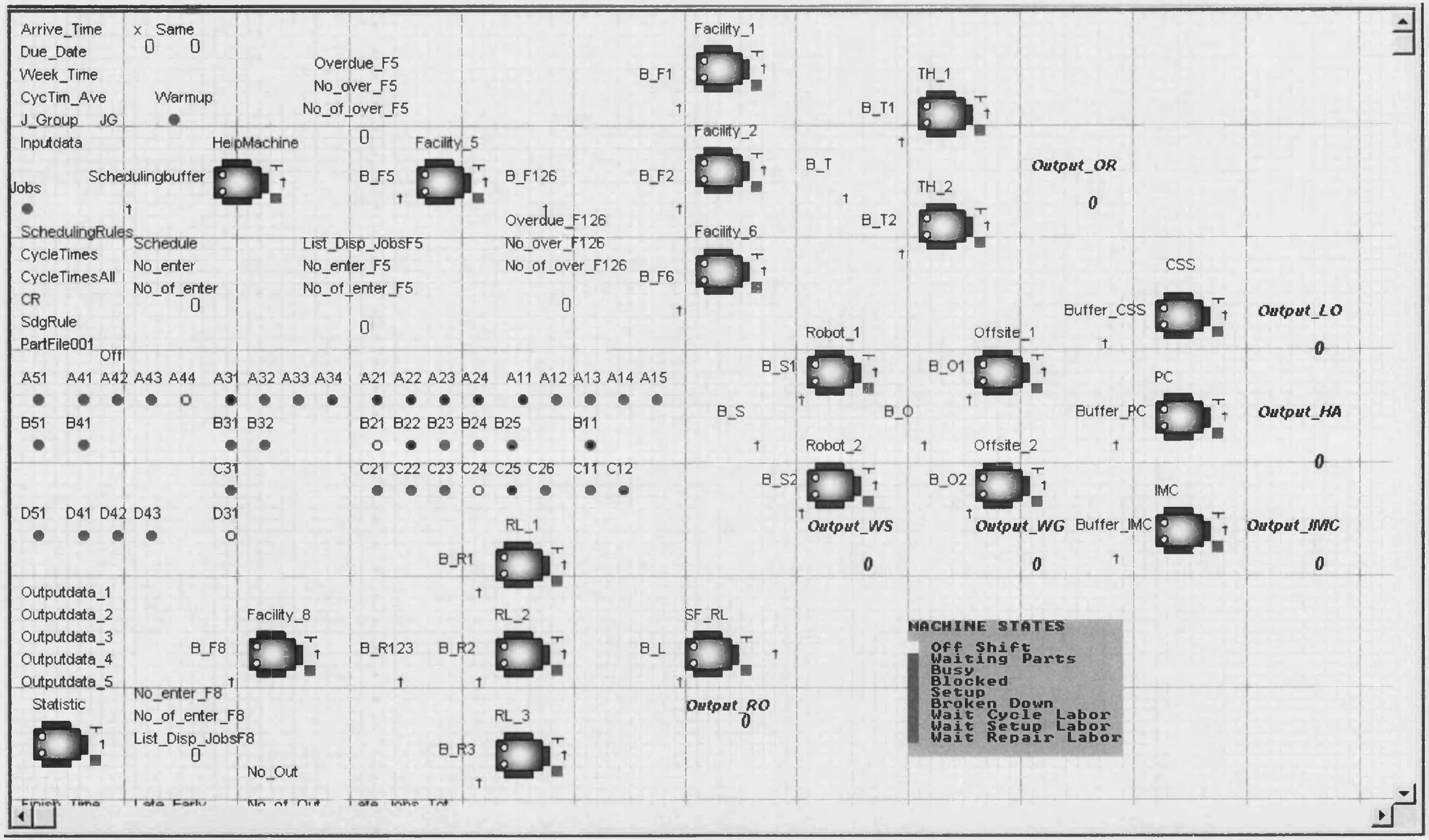


Figure 7.37: Layout of Witness model.

CHAPTER 8 INVESTIGATION OF THE PERFORMANCE OF NEW AND EXISTING CHANGEOVER SENSITIVE HEURISTICS OVER A RANGE OF SCENARIOS

8.1 INTRODUCTION

This chapter outlines the main investigation of Changeover Sensitive Heuristics (CSHs) that have taken place during the course of the project. A range of existing as well as new proposed CSHs have been tested for a number of scenarios and under different experimental factors. The experiments have been designed with the aim of finding answers to the research questions outlined in section 8.2. The heuristics tested are described. The experimental factors and the performance measures are discussed. The experimental conditions described in Chapter 7 are set the same throughout the experiments, although the factors are varied. Statistical analysis of the results of the simulation experiments has taken place and the results are discussed and displayed in graphical format. As described in Chapter 7 three main models, Model 18, Model 42a and Model 42b were developed during the course of the project. However, the experiments described in this chapter, focus on discussing the results from Model 42a and Model 42b. It was decided that because Model 18 is embedded in Model 42a, not to use the results of Model 18. The results from Model 18 are available in Appendix H (please refer to attached CD-ROM), but only the details of Model 42a and Model 42b are presented in this chapter.

The preceding chapters have answered the research objectives listed here:

- Investigate *existing* scheduling *approaches* and *heuristics* currently applied.
- Analyse the extent of the use of *scheduling systems* and other approaches in industry.
- Examine the effectiveness of *existing* scheduling approaches.
- Ascertain the *interdependence* between *scheduling and sequencing* and *changeovers.*
- Develop *simulation models,* which properly reflect the variables found in real industrial changeover environments.

The final objectives covered in this chapter were:

- Investigate a range of heuristics including;
    - *Simple* dispatching rules.
    - *Semi-* changeover sensitive heuristics.
    - *Existing* changeover sensitive heuristics.
    - *New* changeover sensitive heuristics.
- Investigate the performance of the heuristics under different experimental factors, such as;
    - Different levels of *processing times* (e.g. longer and shorter).
    - Different changeover times, such as *major*, *minor* and *none.*
    - Different levels of *changeover time reduction.*
    - Increased batch sizes (increased *utilisation*).
    - Studying a range of different *performance measures.*

In order to achieve this, these objectives were formulated into precise research questions, which are outlined in the next section.

8.2 RESEARCH QUESTIONS INVESTIGATED

This section outlines the research questions being investigated through the simulation experiments.

a) If changeover times could be reduced through design changes and product grouping techniques, what effect would this have on the scheduling and sequencing principles applied? i.e.; to properly benefit from changeover time reduction would different scheduling approaches be advantageous and if so what type and which heuristics would have the greatest impact?

b) How do the different heuristics perform in particular on:
    a. Comparative performance between all heuristics, non-CSHs and CSHs.
    b. Comparative performance between CSHs.
    c. Comparative performance between product family, sub-family and job focussed heuristics.

d. Performance of proposed heuristics, which combine product family and sub-family principles.
e. Performance of exhaustive heuristics compared to non-exhaustive heuristics, for both product family and sub-family heuristics.
f. Impact of different "break" rules, such as non-due date based (e.g. FCFS) and due date based (e.g. CR), on performance of CSHs.

c) What is the impact of changeover time to processing time ratio?
d) Which heuristics perform best for longer or shorter processing times.
e) Effect of scheduling policies on different shop utilisation levels.
f) How do different heuristics perform when compared over the same utilisation levels, i.e. increasing utilisation in shops where rules that may decrease utilisation are applied, such that the same utilisation is achieved both for FCFS and the best performing CSH?
g) In which situations does the shop capacity increase?
h) How do different heuristics compare over different performance measures?
i) How do different heuristics perform for different "types" of product families, e.g. families with majority of longer jobs compared to families with shorter jobs?
j) How do different heuristics compare when the number of product sub-families is increased?

The research questions outlined here have all been considered when designing the experimental testing. The main emphasis of the research has been to investigate the performance of the proposed CSHs, compared to existing heuristics, with special emphasis on "3-stage product family heuristics", as well as studying which heuristics perform well for which scenario and situation.

In addition to the research questions addressed above the impact of different time horizons (arrival distribution of jobs) on a range of heuristics has also been investigated. However, this study is separate and has not been incorporated in this thesis. For details of this, please refer to Eriksson *et al.* (2005 and 2006).

8.3 HEURISTICS INVESTIGATED

In total ten heuristics (H1 to H10) and two semi-heuristics (SH1 and SH2) are investigated. This section explains the operation of each of them, why a particular heuristics has been chosen and previous application and performance, if applicable.

H1. Heuristic 1: First Come First Served (**FCFS**)

FCFS selects jobs in order of job arrival. It is a common benchmark and is currently in use within the case study company.

SH1. Semi-Heuristic 1: FCFS and ChangeOver time reduction (**FCFS-CO**)

This is a *scenario* rather than a different heuristic compared to the FCFS heuristic. FCFS-CO operates in the same manner as FCFS. However, the difference with this scenario is that changeover time reduction takes place when jobs from the same product family or the same sub-product family arrive in sequence. The reason to apply this is to investigate the impact of keeping the current heuristic, which is FCFS, and focus on reducing changeover times with design changes only and not applying different sequencing heuristics. FCFS-CO is called a *semi-heuristic.*

H2. Heuristic 2: Critical Ratio (**CR**) (Incorporates due dates)

Critical ratio is calculated as; due date less current date and then divided by the remaining lead time. The job with the lowest CR value is selected. The CR rule is fairly common and was the best performing heuristic in a previous study of a similar job shop problem (Eriksson et al, 2005).

SH2. Semi-Heuristic 2: CR and ChangeOver time reduction (**CR-CO**) (Incorporates due dates)

Like the testing of FCFS-CO, the CR-CO is a *scenario* rather than a different heuristic. CR-CO operates in the same manner as CR and incorporates changeover reduction. The aim being to investigate the impact of changing to a due date based heuristic, reducing changeover times with design changes only and not considering CSH heuristics. CR-CO is called a *semi-heuristic.*

H3. Heuristic 3: Changeover Sensitive Heuristic 1 (**CSH1**)

CSH1 scans the queue for a job from the same product family as that job which has just been scheduled. When there is no identical job in the queue the CSH1 heuristics selects according to FCFS rule.

H4. Heuristic 4: Changeover Sensitive Heuristic 1-K (**CSH1-K**)

CSH1-K uses the same principle as CSH1 with the difference that when K jobs from the same product family are scheduled in sequence CSH1-K takes the next job according to FCFS rule and then resumes to CSH1 policy. When there is no identical job in the queue and the value of K has not been reached, the next job is selected according to FCFS policy. For Model 42a, K is set to **3** and for Model 42b K is set to **5**. This is because the batch size of Model 42a and Model 42b are very different and applying the same K value was not appropriate.

H5. Heuristic 5: Changeover Sensitive Heuristic 1-K-CR (**CSH1-K-CR**)

This heuristic operates as CSH1-K, except that when the value of K has been reached, the next job from a different product family is chosen according to the job in the queue that has the lowest CR value.

H6. Heuristic 6: Changeover Sensitive Heuristic 2 (**CSH2**)

This heuristic scans the queue for a job from the same sub-product family (identical) as the scheduled job. When there is no job from the same sub-product family in the queue, the CSH2 heuristic selects according to FCFS rule.

H7. Heuristic 7: Changeover Sensitive Heuristic 2-K (**CSH2-K**)

CSH2-K uses the same principle as CSH2 with K jobs from the same sub-product family being scheduled in sequence CSH2-K and then the next job from another sub-product family according to FCFS rule is selected and the CSH2 policy resumes. When there is no job from the same sub-family in the queue and the value of K has not been reached, the next job is selected according to FCFS policy. For Model 42a, K is set to **3** and for Model 42b K is set to **5**.

H8. Heuristic 8: Changeover Sensitive Heuristic 2-K-CR (**CSH2-K-CR**)

This heuristic operates the same as CSH2-K, except that when the value of K has been reached, the next job from a different sub-product family is chosen according to the job in the queue that has the lowest CR value.

H9. Heuristic 9: Changeover Sensitive Heuristic 1 and 2 (**CSH12**)

CSH12 sequences all jobs from the same *sub-product family*, choosing the first job according to the job that is first in the queue. The next job is thereafter selected according to the first job in the queue that belongs to the same *product family*. When there is no job from the same sub-product family or product family waiting in the queue, the next jobs is chosen according to FCFS and the process is repeated with all jobs from a specific sub-product family and thereafter another sub-product family within the same product family etc.

H10. Heuristic 10: Changeover Sensitive Heuristic 1 and 2 – K (**CSR12-K**)

CSH12-K uses the same principle as CSH12 with the difference that when K jobs from the same sub-product family are scheduled in sequence CSH2-K takes the next job from another *sub-product family* within the same *product family* according to FCFS rule. CSH12 selects all jobs from the same product family before swapping to the next according to FCFS. When there is no job from the same sub-family in the queue and the value of K has not been reached, the next job is selected according to FCFS policy. For Model 42a, K is set to **3** and for Model 42b K is set to **5**.

The new heuristics are the two heuristics that combine product family and sub-product family scheduling, which are CSH12 and CSH12-K. The CSR12 and CSR12-K are three-stage heuristics, meaning that they sequence jobs according to the sub-product family and product family that the jobs belong to. As far as the authors are aware, no previous research has separated CSHs for product family and sub-product family sequencing and furthermore compared those approaches to consider both product family and sub-product family, such as the CSH12 heuristics. Variants of CSH1, a two-stage heuristic, have previously been applied, for example, by Jacobs and Braggs (1988), Flynn (1987a), Flynn (1987b) and Mahmoodi and Dooley (1991).

However, in this research CSH1 represent product family scheduling whereas CSH2 is based on the same principle, but sequence according to sub-product family, hence comparing the difference between scheduling product families and sub-product families. Both exhaustive and non-exhaustive versions of CSH1, CSH2 and CSH12 have been applied. Furthermore, CSH1-K-CR and CSH2-K-CR, apply the CR heuristic as a "break" strategy, rather than FCFS, which is used in CSH1-K, CSH2-K and CSH12-K. Two simple or single-stage heuristics have been applied, the FCFS as it is the current heuristic applied at the company and the CR heuristics, which previously had performed well. Two semi-heuristics are also tested, the FCFS-CO and the CR-CO heuristic. The semi-heuristics are incorporated to investigate how simple heuristics compare if changeover time has been dealt with through organisational and design improvements, but changeover scheduling heuristics have not been addressed.

8.4 EXPERIMENTAL FACTORS

This section outlines the experimental factors under which the testing has taken place.

8.4.1 Processing time

The processing times vary according to a user defined distribution for each one of the facilities. The distributions have been determined by data collection from the case study company. Overall the processing times range from 1 day (or 8 hours) to processing times of a couple of weeks. Commonly processing times are about 5 days (40 hours), although it varies for different facilities. The simulation model that replicates those processing times is named, Model 42a. However, it was of interest to investigate the impact of different levels of processing times. Therefore, a second model, named Model 42b, was created. In this model the processing times have been reduced to 10% of the original processing times, resulting in processing times ranging from 48 minutes to about 480 min (1 day or 8 hours). This implies that the number of jobs generated for Model 42b is increased by a factor of ten.

To conclude, two levels of processing times have been tested. Previous studies have commonly applied processing time distributions, such as *Third-order Erlang* (Mahmoodi and Dooley, 1991 and Wemmerlöv and Vakharia, 1991, *Uniform* (Baker, 1999) or *Exponential* (Flynn, 1987a, Flynn, 1987b and Kim and Bobrowski, 1997) processing times, but rarely has the same study investigated different levels of processing times.

8.4.2 Changeover time reduction

The emphasis of this research has been to investigate the effect of *changeover time reduction*. In other words, how does changeover time reduction affect the performance of the job shop and what are the scheduling and sequencing requirements when jobs are grouped into product families and sub-product families? After discussion with experts at the case study company, certain characteristics of the changeovers could be concluded. The changeover time between jobs varied depending on whether the change was between jobs from different product and sub-product families or between jobs within the same product or sub-product family. There is deemed to be a *major reduction* in changeover time if two jobs from the same sub-product family are scheduled in sequence. There is a *minor reduction* in changeover time if two jobs from different sub-product families belonging to the same product family are scheduled in sequence. If a job is followed by a job from a different product family there is no changeover time reduction as it is assumed that a full changeover is necessary.

Naturally incorporating changeover time increases the total throughput time (processing time and changeover time) of the job. The data gathered within this particular industrial sector indicated that the shorter the total throughput time for a job the longer the percentage changeover time tended to be. The total changeover time, as shown in Table 8.1, consists of set-up time, take-down (or run-down) time and internal set-up (adjustments). Internal set-up within this company is the set-up time that takes place between different test programs and the adjustment to the set-up during a test, e.g. changing positions of electrical cables.

Test time (no. of days)	Major changeover reduction between jobs within the same sub-product family	Minor changeover reduction between jobs within the same product family
1 - 4 day(s)	33%	10.0%
5 - 9 days	25%	7.5%
10 - 19 days	20%	6.0%
20 - days	15%	4.5%

Table 8.1: Major and minor changeover time reduction.

8.4.3 Changeover time reduction to processing time ratio

Two levels of changeover time reduction to processing time ratio were tested. The first scenario does not incorporate reduction in changeover time at all, but is at a minimum of *no changeover time reduction (0%)*. The reason to run the experiments with no changeover time reduction is that this is the current situation at the case study company and hence the benchmark scenario. Even though FCFS is the main benchmark, it is interesting to test all of the heuristics for this scenario as this determines the performance of CSHs in an environment without changeover time reduction. This scenario serves as a comparison when changeover time reduction is considered. The scenario without changeover time reduction gives an indication of how the current practice at the shop could possibly be improved through different scheduling and sequencing approaches alone, without investment of family grouping of products or design changes for changeover time reduction. The second level of changeover time reduction applied to the experiments is *full changeover time reduction (100%)*. Hence, if changeover times are reduced according to Table 3 they represent a maximum or 100% changeover time reduction. For example, if the test time is one (1) day, the maximum *major* (between product families) changeover time reduction is 33.0% and the maximum *minor* (between sub-product families) changeover time reduction is 10.0%.

8.4.4 Shop load (utilisation) and number of arriving jobs

Number of arriving jobs

The number of jobs arriving every four weeks is 16 for Model 42a, based on the data collection at the case study company. In Model 42b, which has the lower processing time level, 160 jobs arrive every four weeks. Experiments have also been performed where the number of jobs arriving is increased. This is explained under the heading "Shop load (utilisation)".

Shop load (utilisation)

The utilisation level in the shop is validated according to the real system. The overall utilisation of Model 42a and Model 42b is 71% and 73% respectively. The utilisation comparison for each of the 17 facilities is displayed in Figure 8.1 and 8.2. Most previous research has assumed high utilisation of the shop or machine tested, such as 80%-90% utilisation. However, it should be said that this can be an unrealistically high utilisation of machines in a real environment and few examples have investigated shops with lower utilisation, as it often seems to be considered that in such cases scheduling and sequencing is not of importance.

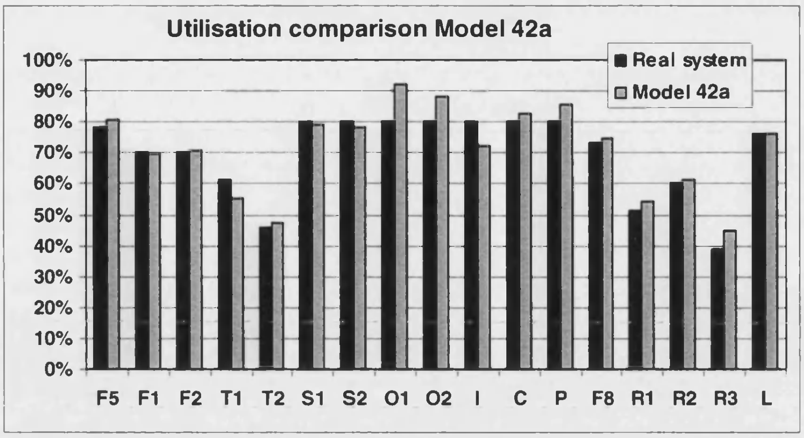


Figure 8.1: Utilisation comparison of data collection and Model 42a.

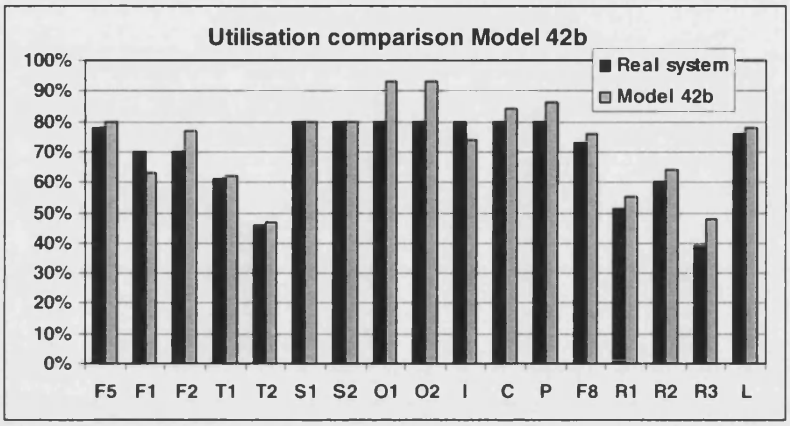


Figure 8.2: Utilisation comparison of data collection and Model 42b.

A further scenario has been added to the experiments that incorporates a different utilisation. When running the experiments, the changeover sensitive heuristics naturally reduce changeover time hence the total processing time will be reduced if changeover time reduction takes place and arrival frequency of jobs are kept the same. This is the effect expected by applying CSHs and implies that more capacity will be available in the shop. Therefore, the question that arises is what can this extra capacity be used for? Meaning how many more jobs can be tested (produced) with design changes for changeover, family grouping and applying changeover sensitive heuristics?

To investigate this, a scenario was created, where the number of jobs is increased and all the heuristics are again run for this scenario to determine how they cope with increased utilisation of the shop. To increase the utilisation, the heuristic that reduces the utilisation most for Model 42a and Model 42b respectively, are run again with a larger number of jobs arriving in each batch. When the utilisation has reached the original level according to Figure 8.1 and 8.2 all the experiments are re-run with this increase in job arrivals. The increase for Model 42a is 12.5 % and Model 42b is 22%. The reason that Model 42a cannot cope with the same increase as Model 42b is it has longer processing times than Model 42b and therefore it is difficult to fit more jobs in, whereas the shorter processing times in Model 42b make it easier to fill gaps in the schedule.

8.4.5 Summary of experimental factors

- *Twelve* heuristics (including two semi-heuristics)
- *Two* levels of processing times (100% and 10%)
- *Three* levels of changeover time reduction (major, minor and none)
- *Two* levels of changeover time reduction (none and 100%)
- *Two* levels of batch size (original and increase in batch size)

8.5. PERFORMANCE MEASURES

Performance measures are used to assess the quality of a schedule and for this research, multiple performance measures were investigated. A total of ten performance measures were considered and they are summarised in Table 8.2. The criteria were selected on the basis of their relevance to the industrial environment which was studied. These measurements included criteria such as, tardiness, average time the job spent in the system and percentage of late jobs. The percentage of late jobs was not only studied as an overall measure, but the variations in the percentage of late jobs between different product families were also considered.

PERFORMANCE MEASURES	DEFINITION AND EXPLANATION OF PERFORMANCE MEASURES
Non due date related performance measures	
Average time in process (ATP_j)	This is the average time the jobs have spent going through the process.
Work-In-Progress (WIP)	This is the average number of jobs being processed, in the progress of going through the shop.
Total Sum of Changeover Time Reduction (TSCTR)	This is the sum of the changeover time reduction of all facilities. That is the total changeover time from the 17 facilities F5, F1, F2, T1, T2, S1, S2, O1, O2, C, P, I, F8, R1, R2, R3 and L.
Due date related performance measures	
Tardiness (T_j)	Tardiness is the positive lateness a job incurs if it is completed after its due date. Therefore, the difference between tardiness and lateness is that tardiness is never negative.
Earliness (E_j)	Earliness is the positive lateness a job incurs if it is completed before its due date. Total earliness is the sum of the earliness of the jobs that have gone through the system. It is important to realise that although earliness may sound like a positive measure, it could be considered a negative measure in a just-in-time system.
Total number of tardy jobs (N_T)	The total number of jobs that have violated their due dates.
Number of tardy jobs for ***Product Family A*** *(N_A)*	The total number of jobs from product family A that have violated their due dates.
Number of tardy jobs for ***Product Family B*** *(N_B)*	The total number of jobs from product family B that have violated their due dates.
Number of tardy jobs for ***Product Family C*** *(N_C)*	The total number of jobs from product family C that have violated their due dates.
Number of tardy jobs for ***Product Family D*** *(N_D)*	The total number of jobs from product family D that have violated their due dates.

Table 8.2: List of performance measures studied.

8.6 EXPERIMENTAL SCENARIOS

Table 8.3 displays the experimental scenarios that have been tested. Twelve heuristics, including the semi-heuristics of FCFS-CO and CR-CO are tested over three scenarios. *Scenario 1* does not consider changeover time reduction, whereas *Scenario 2* applies a full changeover time reduction (100%). *Scenario 3* also has 100% changeover time reduction. However, to increase the utilisation when changeover time reduction takes place, *Scenario 3* incorporates an increase in the batch size of job arrivals. Model 42a has a 12.5% increase in batch size and Model 42b has a 22% increase in batch size. The experiments run for both models are the same except for different increases in the batch size and different processing time levels. In Table 8.3, three experiments are shaded light grey and three experiments are shaded dark grey. This is to indicate that the three light grey experiments and the three dark grey experiments are actually the same, because none of those incorporate changeover time reduction. FCFS and CR do not incorporate changeover time reduction in *Scenario 3*, as those heuristic are incorporated to study behaviour where no changeover time reduction takes place. However, *Scenario 3* is different from *1* and *2* for FCFS and

CR, as the number of jobs has increased. The number of experiments is therefore 32 times two, adding up to a total of 64 experiments, 32 according to Table 8.3 and 32 according to Table 8.4.

No.	Scheduling Heuristic	Scenario 1	Scenario 2	Scenario 3
		0% CO Reduction	100% CO Reduction	100% CO Reduction Job Increase
1	FCFS Benchmark	X	X	X
2	FCFS-CO	X	X	X
3	CR	X	X	X
4	CR-CO	X	X	X
5	CSH1	X	X	X
6	CSH1-K	X	X	X
7	CSH1-K-CR	X	X	X
8	CSH2	X	X	X
9	CSH2-K	X	X	X
10	CSH2-K-CR	X	X	X
11	CSH12	X	X	X
12	CSH12-K	X	X	X

Table 8.3: Experimental scenarios for Model 42a.

No.	Scheduling Heuristic	Scenario 1	Scenario 2	Scenario 3
		0% CO Reduction	100% CO Reduction	100% CO Reduction Job Increase
1	FCFS Benchmark	X	X	X
2	FCFS-CO	X	X	X
3	CR	X	X	X
4	CR-CO	X	X	X
5	CSH1	X	X	X
6	CSH1-K	X	X	X
7	CSH1-K-CR	X	X	X
8	CSH2	X	X	X
9	CSH2-K	X	X	X
10	CSH2-K-CR	X	X	X
11	CSH12	X	X	X
12	CSH12-K	X	X	X

Table 8.4: Experimental scenarios for Model 42b.

8.7 RESULTS, STATISTICAL ANALYSIS AND DISCUSSION

After each experiment the results were collected in reports produced by the Witness software. The results from Witness were analysed in MS Excel and statistical analysis of ANOVA (ANalysis Of VAriance between groups) tests were run applying SPSS (Statistical Package for the Social Sciences), with a significant level of 0.05. The Post Hoc multiple comparisons chosen were LCD and Bonferroni (recommended by Robinson, 2004). Full reports of this are included in Appendix I (please refer to attached CD-ROM).

The results are plotted with their standard deviation in Figure 8.4 to 8.31. This means that for two heuristics to perform significantly different the top of the bars should not cross over anywhere within their standard deviations. In several of the graphs in Figure 8.4 to 8.31, the standard deviation range is very narrow and it is not possible to print it clearly. Therefore, some of the graphs do not start at zero on the Y-axis.

Table 8.4 outlines the performance measures, their abbreviations and units, which are applied in the graphs. The heuristics have been numbered from 1-12, according to Table 8.5. Bear in mind that the tardiness measure is displayed as an absolute value, the positive tardiness, meaning the best performing rule according to tardiness is the one closest to zero on the Y-axis. The earliness measure on the other hand is considered to be a better performer the higher it is. However, from a "just-in-time" point of view it could be argued that earliness should also be low, although, this is not the main objective in this case.

Abbreviations	Explanation	Unit measured in
ATP_j	Average Time in Process	Days
WIP	Work-In-Progress	Days
TSCT	Total Sum of Changeover Time	Weeks
T_j	Tardiness	Weeks
E_j	Earliness	Weeks
N_T	Total Percentage of tardy jobs	Percent (%)
N_A	Percentage of tardy jobs for Product Family A	Percent (%)
N_B	Percentage of tardy jobs for Product Family B	Percent (%)
N_C	Percentage of tardy jobs for Product Family C	Percent (%)
N_D	Percentage of tardy jobs for Product Family D	Percent (%)

Table 8.5: Key to performance measure abbreviation.

Five of the performance measures, ATP_j, WIP, TSCT, and E_j, are plotted over the three scenarios for each Model 42a and Model 42b. Whereas, percentage of tardy jobs (N_T, N_A, N_B, N_C and N_D) are all plotted in the same graph, one for each scenario.

Figure 8.4 to 8.11, display the graphs associated with Model 42a and Figure 8.12 to 8.19 the graphs associated with Model 42b. Thereafter, Figure 8.20 to Figure 8.31, displays a third set of graphs. These graphs compare the performance measures over even utilisation. Meaning that, because the FCFS and CR heuristics, have no changeover time reduction, for the FCFS and CR heuristics the data from *Scenario 1* is compared with the data from *Scenario 3* for all other heuristics. The utilisation of *Scenario 3*, for the best performing CSH, is equivalent to the utilisation of the benchmark model of *Scenario 1* and the FCFS heuristics, hence creating a fair comparison when the utilisation is evenly distributed for all heuristics.

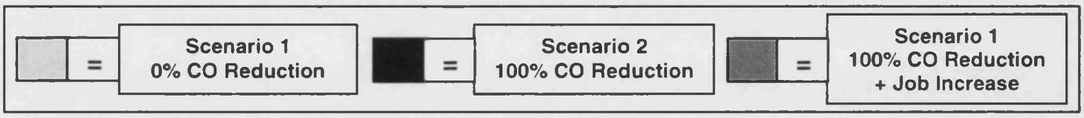
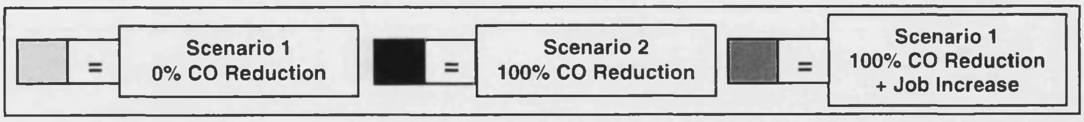


Figure 8.3: Key to graphs in Figure 8.4 to 8.8, Figure 8.12 to 8.16 Figure 8.20 to 8.24 and Figure 8.26 to 8.30.

8.7.1 Results from Model 42a (Figure 8.4 to 8.11)



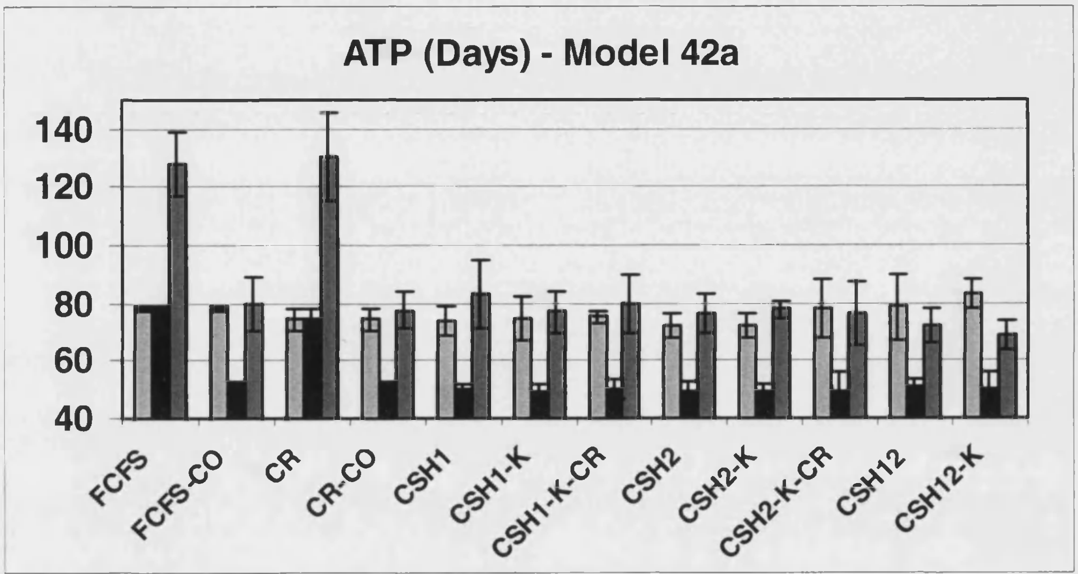


Figure 8.4: Model 42a Plot of ATP (Average Time in Process (Days)) for *Scenario 1, 2 and 3*, with standard deviations.

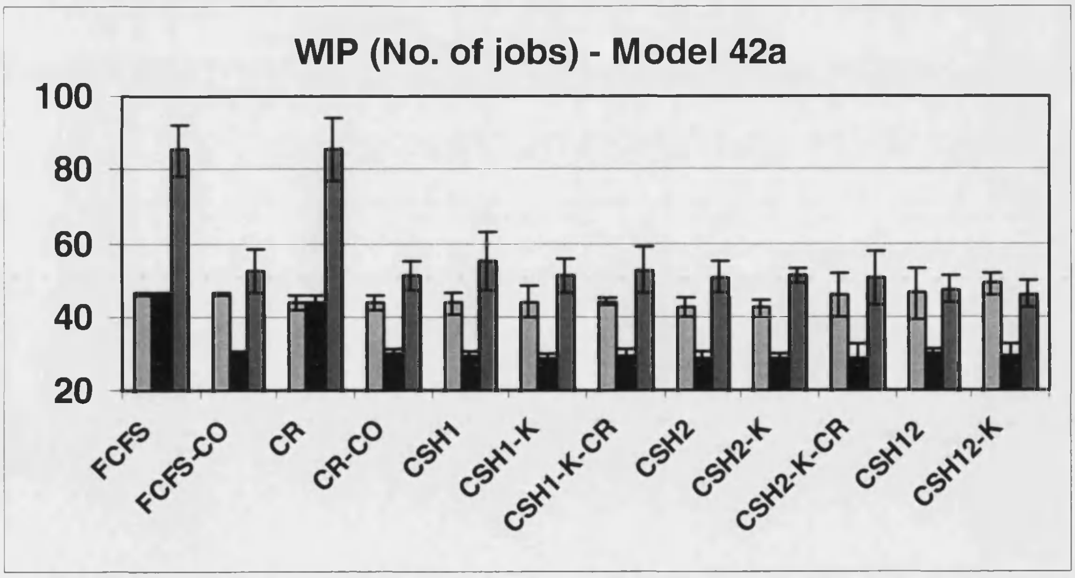


Figure 8.5: Model 42a Plot of WIP (Work-In-Progress (No. of jobs)) for *Scenario 1, 2 and 3*, with standard deviations.

Figure 8.4 and 8.5 displays the ATP and WIP measures from Model 42a for the three scenarios. It is apparent from these graphs that when more jobs (12.5% more and Scenario 3) can be processed in the shop if CSHs are applied. Neither FCFS nor CR perform well on Scenario 3, but instead the ATP and WIP measure more than doubles. On the other hand the FCFS-CO and CR-CO show a performance similar to the changeover sensitive heuristics.

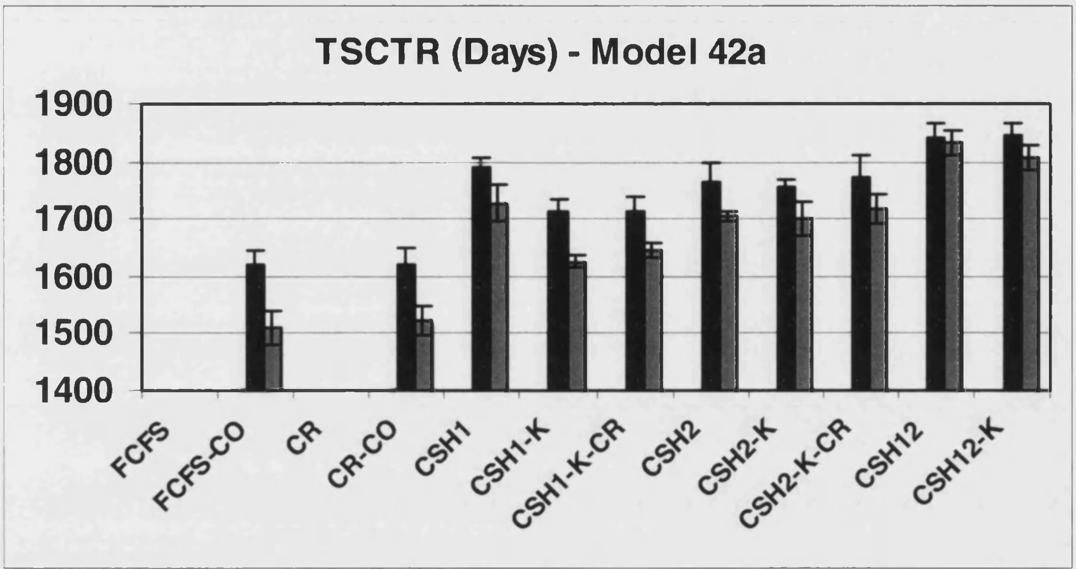


Figure 8.6: Model 42a Plot of TSCTR ((Total Sum of Changeover Time Reduction (Days)) for *Scenario 1, 2 and 3*, with standard deviations.

Regarding reduction of changeover time (Figure 8.6) the new combined heuristics CSH12 and CSH12-K show the highest reduction in changeover time. For this measure the FCFS-CO and CR-CO cannot compete with the CSHs and certainly not with CSH12 and CSH12-K. FCFS and CR do not show any reduction (they are zero) as those models do not incorporate changeover time reduction.

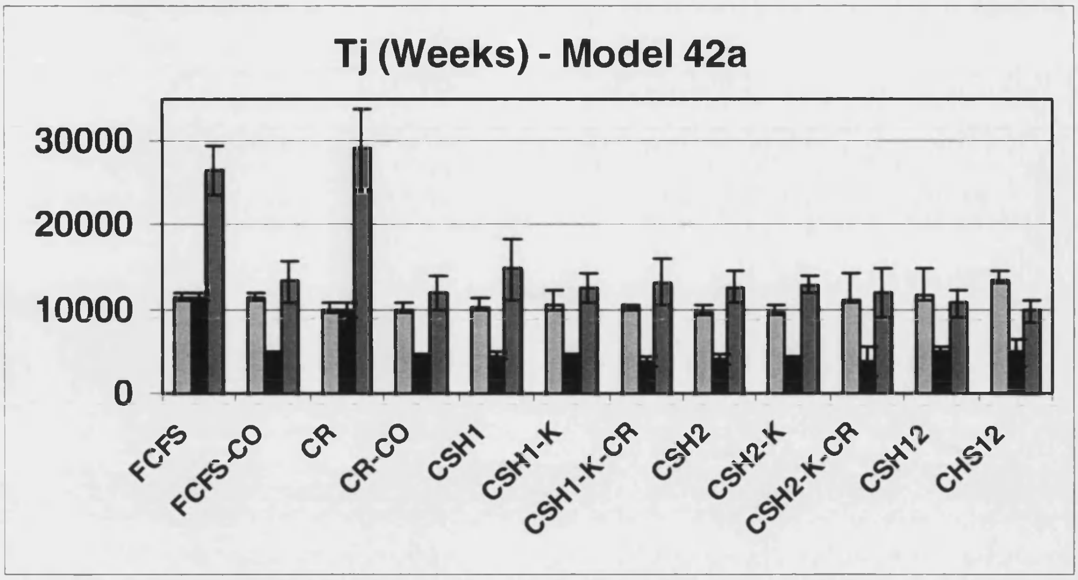


Figure 8.7: Model 42a Plot of Tj (Tardiness (Weeks)) for *Scenario 1, 2 and 3*, with standard deviations.

The tardiness measure for Model 42a show a similar performance for all heuristics, except for the simple heuristics FCFS and CR, which cannot cope with an increase in jobs.

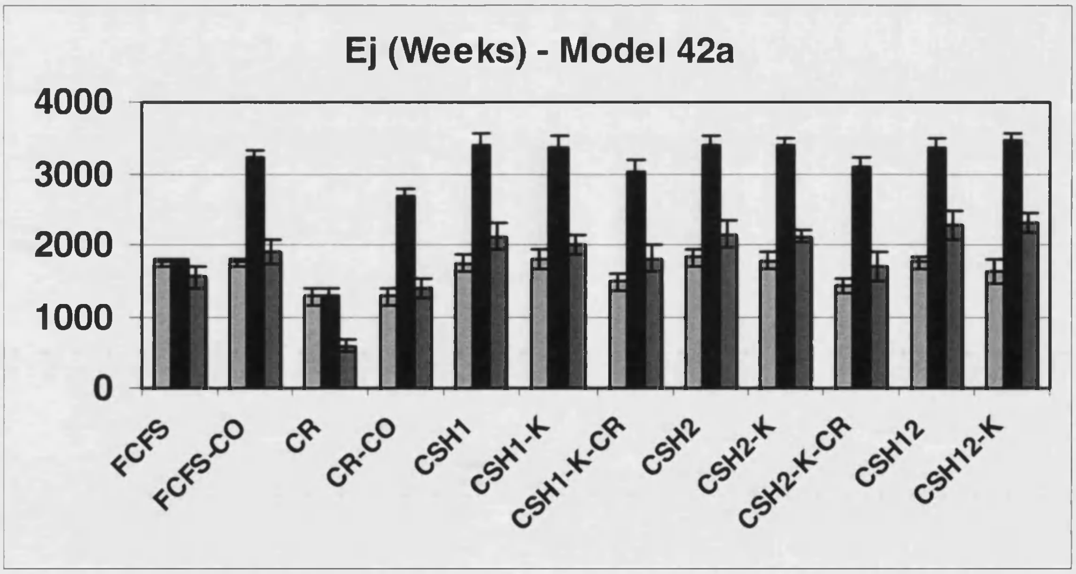


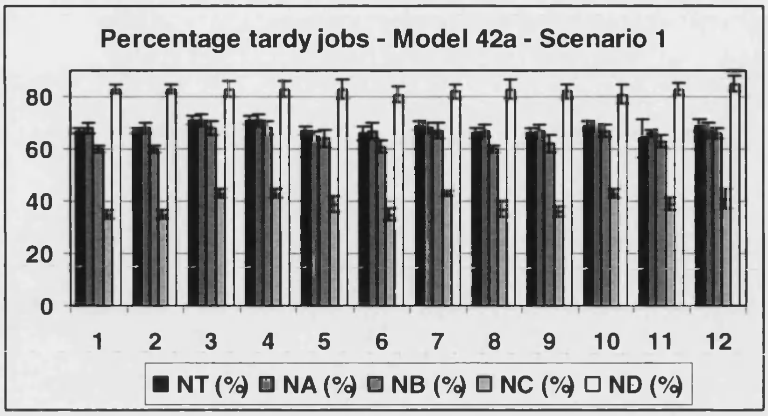
Figure 8.8: Model 42a Plot of Ej (Earliness (Weeks)) for *Scenario 1, 2 and 3*, with standard deviations.

The CSHs and also the semi-heuristics show a similar performance for earliness. The worst performer here is the simple CR. However, this is because CR does not tend to schedule jobs so that they are too early, but instead so that they are close to the due date (JIT).

Several of the measures in Model 42a do not show a large discrepancy even though different heuristics are applied. ATP, WIP, Tj and Ej all show similar performance for any of the heuristics over each scenario. Only FCFS and CR, which do not consider changeover time, are different and show a worse performance overall. This is especially significant for Scenario 3, where FCFS and CR show that they cannot cope with the increase of jobs. TSCTR displays more of a difference between the CSHs. This measure clearly shows the benefit of CSHs displaying a higher reduction of changeover time. FCFS-CO and CR-CO, which incorporates changeover time cannot reduce changeover time as much as the CSHs. Regarding the TSCTR measure, the best performing CHSs are CSH12 and CSH12-K followed by CSH1. The non-exhaustive heuristics CSH1-K and CSH1-K-CR do not reduce changeover as much as the exhaustive heuristics CSH1.

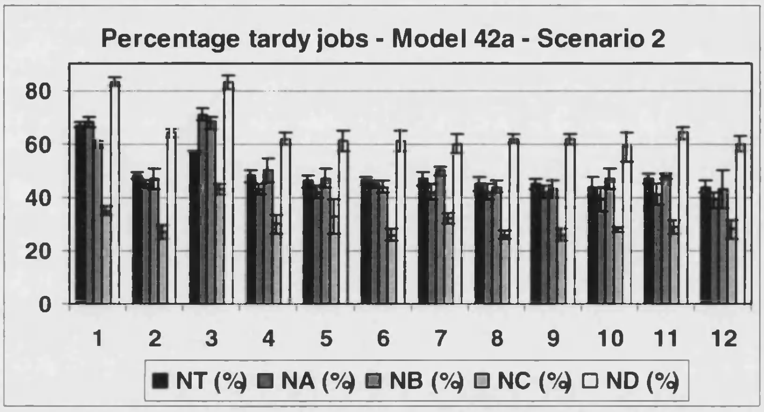
Model 42a

Figure 8.9: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 1*, with standard deviations.



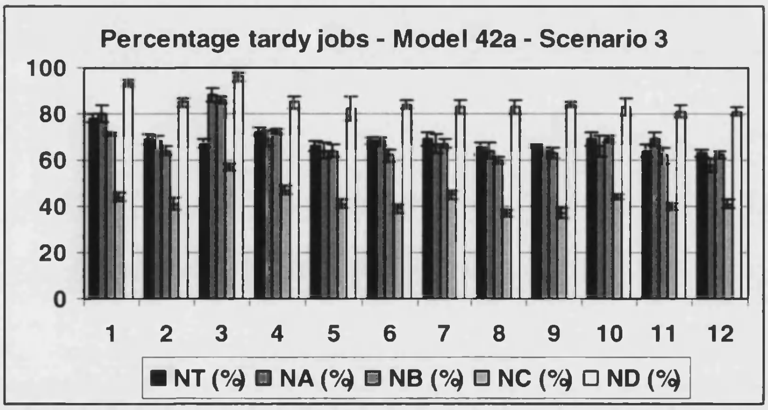
Model 42a

Figure 8.10: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 2*, with standard deviations.



Model 42a

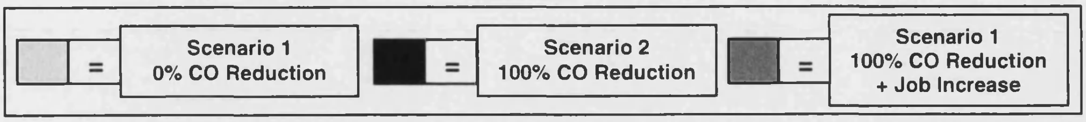
Figure 8.11: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 3*, with standard deviations.



The percentage of tardy jobs shows a low discrepancy over all heuristics for Scenario 1 and Model 42a. As this is the scenario that did not incorporate any changeover time, this result may be expected. Scenario 2, incorporating the changeover time reduction, shows improvement on percentage of tardy jobs for all heuristics, except FCFS and CR, which do not take changeover time into consideration. However, there is no statistically proven difference between any of the CRHs. For Scenario 3 the percentage of tardy jobs has risen compared to Scenario 2. This was expected as the number of jobs entering the model has increased. Again, none of the heuristics perform exceptionally different compared to the others.

N_D which the product family consisting of comparatively longer jobs consistently shows the highest percentage of tardy jobs. This may be because none of the heuristics, not even the CR heuristics that incorporates due dates, prioritises longer jobs. On the other hand, product family N_C, with comparatively shorter processing times, are favoured by all heuristics. It also raises the question, whether due date setting should be different depending of processing time level within the product families.

8.7.2 Results from Model 42b (Figure 8.12 to 8.19)



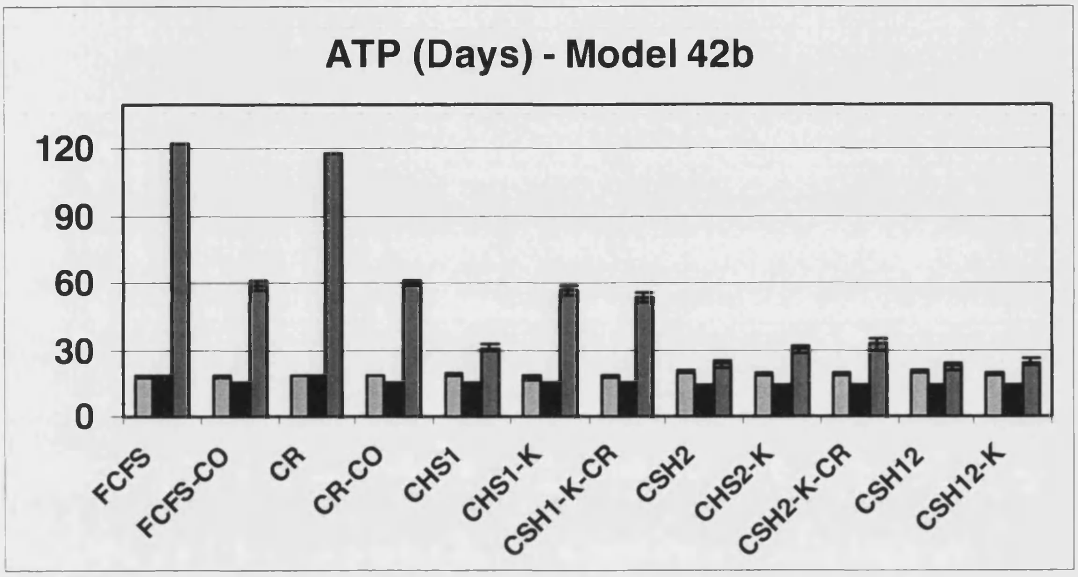


Figure 8.12: Model 42b Plot of ATP (Average Time in Process (Days)) for *Scenario 1, 2 and 3*, with standard deviations.

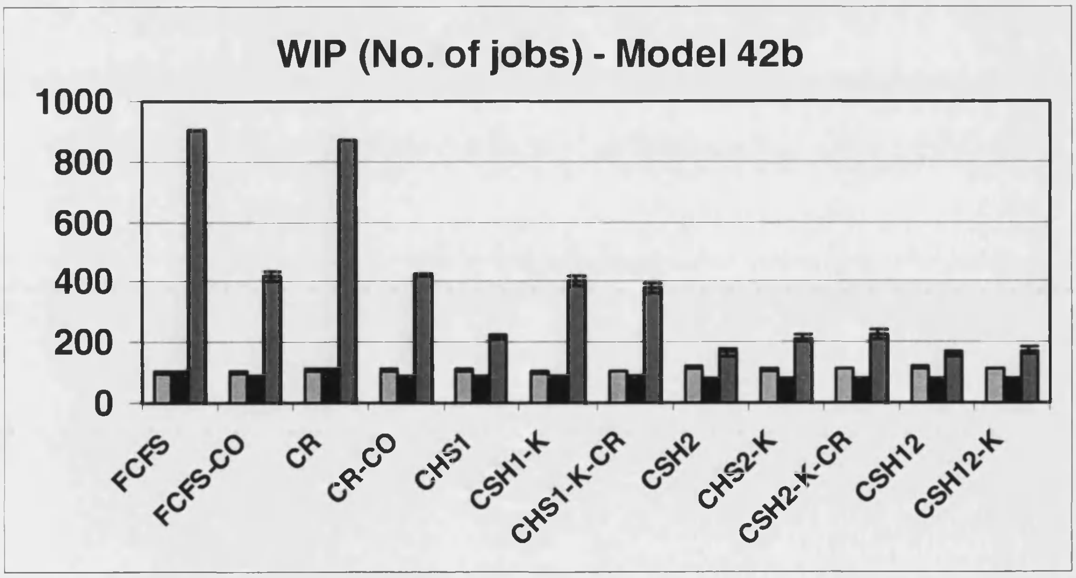


Figure 8.13: Model 42b Plot of WIP (Work-In-Progress (No. of jobs)) for *Scenario 1, 2 and 3*, with standard deviations.

The ATP and WIP measure for Model 42b show that FCFS and CR really cannot cope with the increase of jobs. Furthermore, the heuristics FCFS-CO, CR-CO, CSH1-K and CSH1-K-CR increase over the ATP and WIP measures. On the other hand the non-exhaustive heuristic CSH1 shows a worthy performance. However, best performing rules are the combined CSH12 nd CSH12-K as well as CSH2 that schedules according to sub-product family.

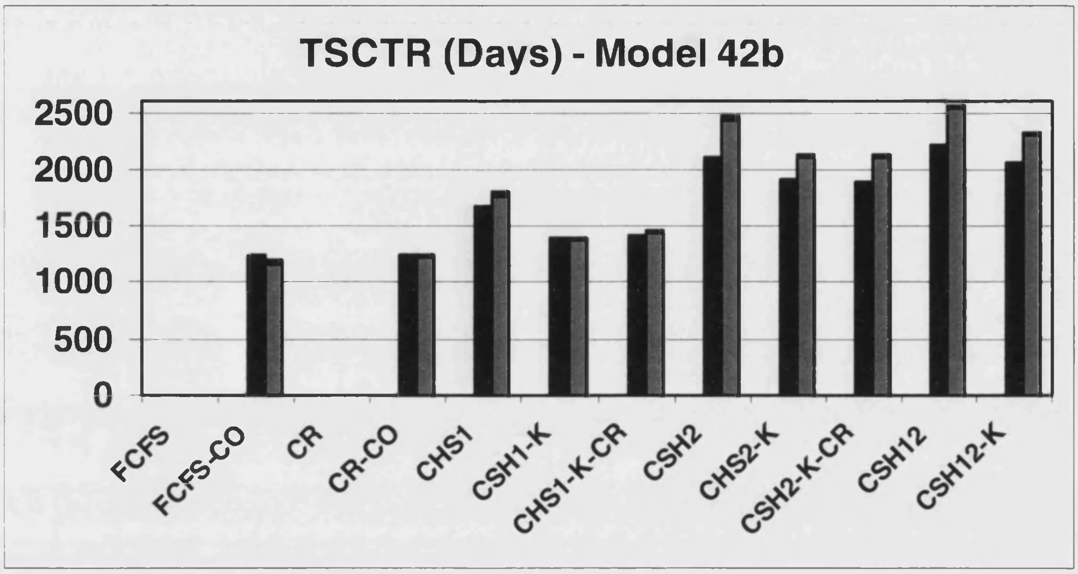


Figure 8.14: Model 42b Plot of TSCTR ((Total Sum of Changeover Time Reduction (Days)) for scenario 1, 2 and 3, with standard deviations.

The best performing heuristics on the TSCTR measure are the two new heuristics CSH12 and CSH12-K. Also the sub-product family heuristic CSH2 has a strong performance.

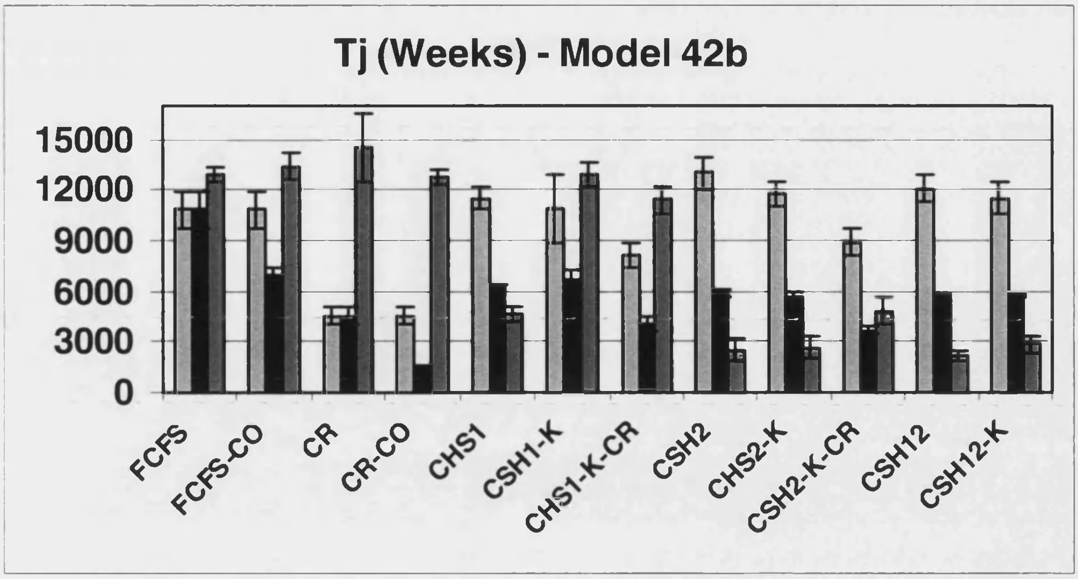


Figure 8.15: Model 42b Plot of Tj (Tardiness (Weeks)) for *Scenario 1, 2 and 3*, with standard deviations.

Scenario 3 is most interesting for the tardiness measure where it is clear that the new heuristics CSH12 and CSH12-K perform best along with CSH2 and CSH2-K.

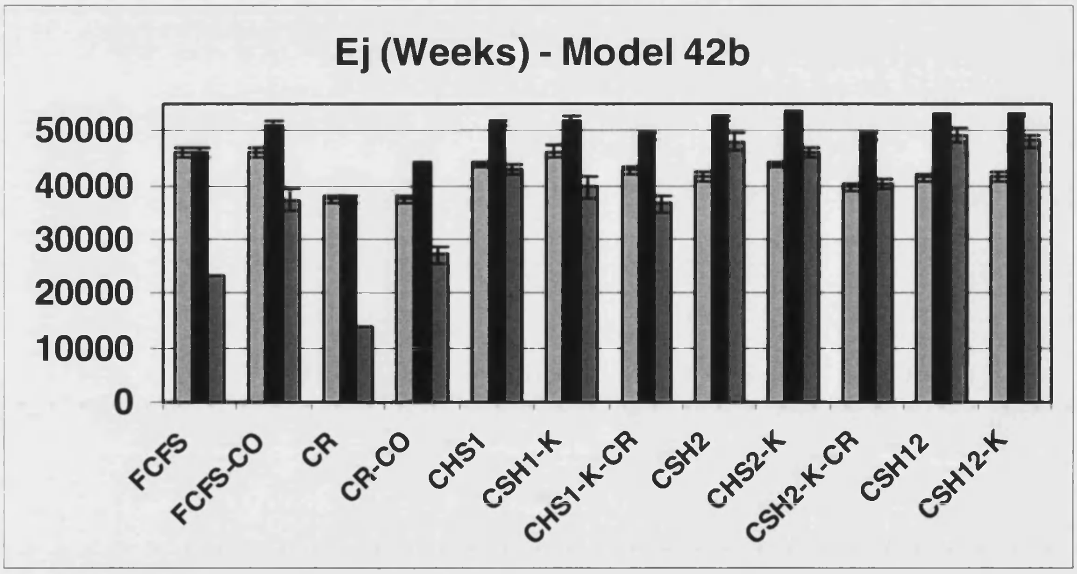


Figure 8.16: Model 42b Plot of Ej (Earliness (Weeks)) for *Scenario 1, 2 and 3*, with standard deviations.

The earliness measure for Model 42b shows a similar performance over most measures, with emphasise on the CSHs. Again, CR shows a low earliness especially for *Scenario 3*, this is due to CR's ability of not scheduling jobs too early.

Analysis of the graphs shows that Model 42b has a larger discrepancy between the different heuristics than Model 42a. The model which contains jobs with shorter processing times benefit more from applying CSHs than Model 42a, where the processing times are ten times as large.

Regarding the ATP and WIP measures, Scenario 1 and 2 show an even performance over all the heuristics. However, it is clear that when more jobs enter the model (Scenario 3) the impact of CSHs is larger. FCFS and CO show the worst performance, because those do not consider any changeover time. The best performing heuristics for the ATP and WIP measures are CSH2, CSH12 and CSH12-K. Similar to the result of Model 42a, CSH1 outperforms CSH1-K and CSH1-K-CR and CSH2 also shows a better performance than CSH2-K and CSH2-K-CR. This implies that the non-exhaustive heuristics perform worse. Especially CSH1-K and CSH1-K-CR show a worse performance, similar to FCFS-CO and CR-CO.

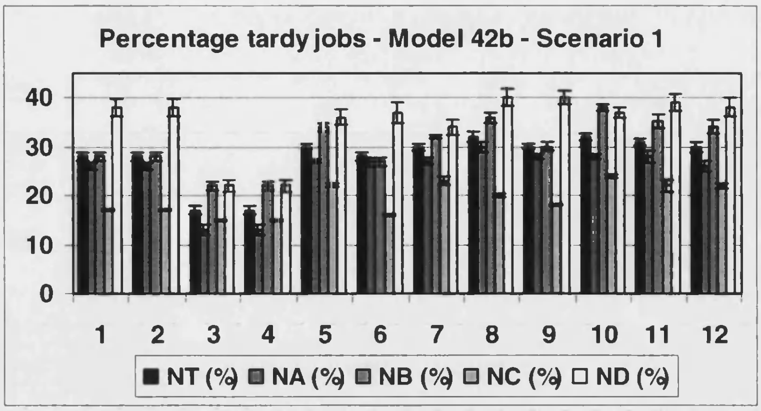
For the TSCTR measure, the result confirms this, again indicating that the exhaustive heuristics perform better than the non-exhaustive.

Regarding the tardiness measure CR-CO shows the overall lowest for Scenario 2. Also, for Scenario 1 the tardiness is low, this is probably because the CR-CO heuristics considers due date. However, this advantage is lost on Scenario 3 where again the exhaustive CSHs cope well with the increase of jobs in the shop.

For earliness CR and CR-CO show the worst performance for Scenario 2, again this is probably due to the fact that due date setting is considered and this results in less early jobs according to a "just-in-time" policy. Otherwise, the earliness measure for Scenario 3 is on a fairly even level across the CSHs.

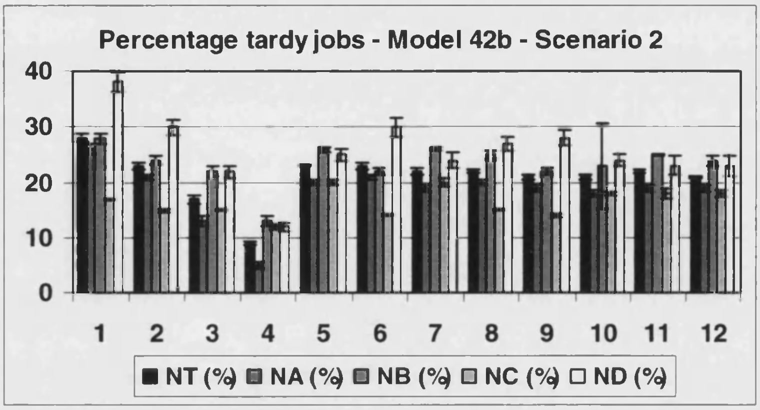
Model 42b

Figure 8.17: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 1*, with standard deviations.



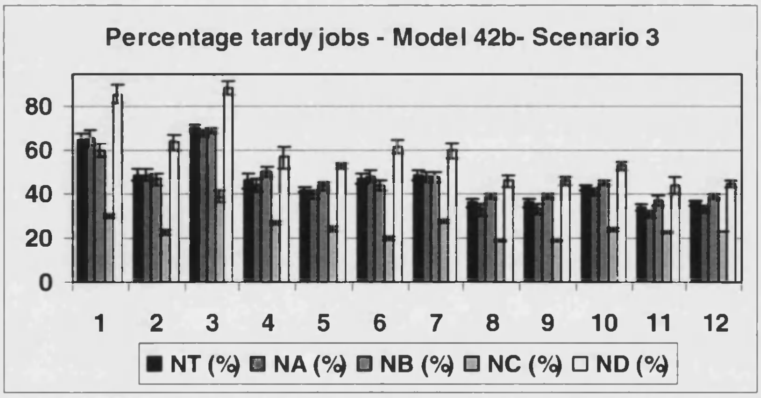
Model 42b

Figure 8.18: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 2*, with standard deviations.



Model 42b

Figure 8.19: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 3*, with standard deviations.



CR and CR-CO show the best performance of percentage of tardy jobs for Scenario 1. For Scenario 2 CR-CO is the clear best performer, most probably because it considers due dates as well as its reducing changeover time. In Scenario 3 the CSHs CSH2, CSH2-K, CHS2-K-CR and the two new heuristics CSH12 and CSH12-K show the lowest number of total tardy jobs.

8.7.3 Results from Model 42a with even utilisation (Figure 8.20 to 8.25)

In order to compare the results with even utilisation over all the heuristics a set of graphs (Figure 8.20 – 8.31) have been plotted, where the results of FCFS (1) and CR (3) from *Scenario 1* are compared to the result from *Scenario 3* of all the other heuristics. This means the heuristics compared will have the same utilisation. The increase in jobs for *Scenario 3* has been determined in order to create the same utilisation as FCFS (1) that *Scenario 1* had.

For Model 42a and the even utilisation graphs most performance measures, except TSCT, show a similar performance. The TSCT measure displays CSH12 (11) and CSH12-K (12) as the best performing heuristics. CSH12 (11) and CSH12-K (12) are also performing best on earliness and in *Scenario 3*.

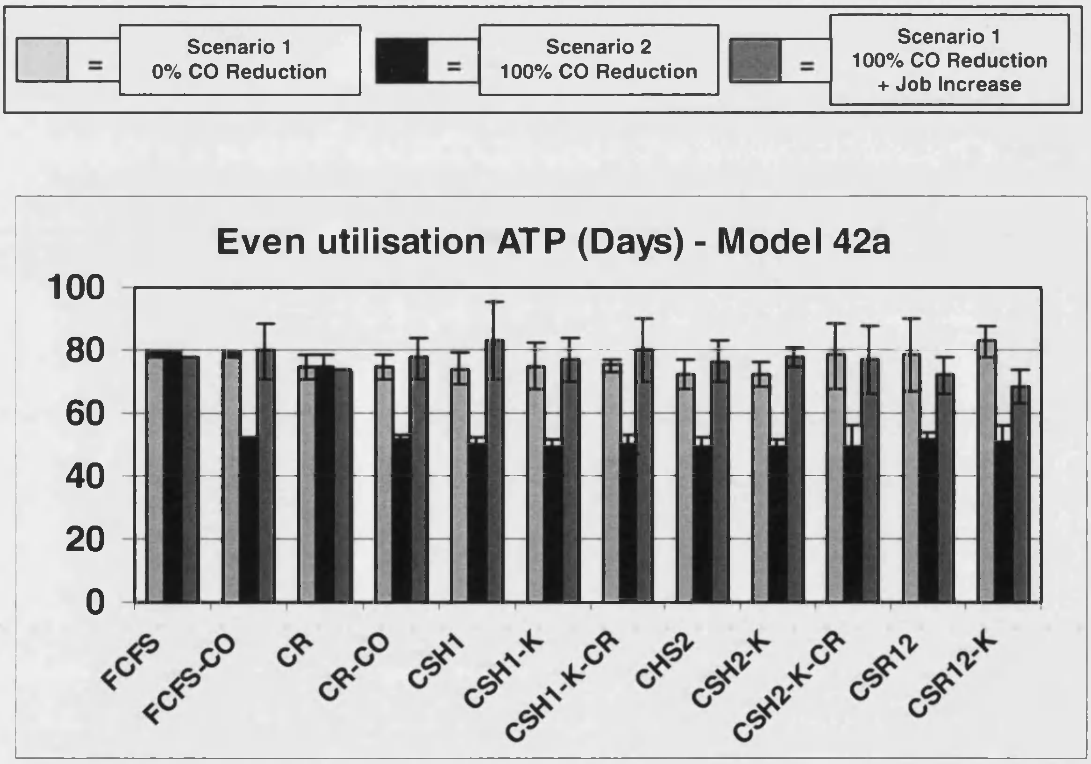


Figure 8.20: <u>Model 42a – Even utilisation</u> plot of ATP (Average Time in Process (Days)) for *Scenario 1, 2 and 3*, with standard deviations.

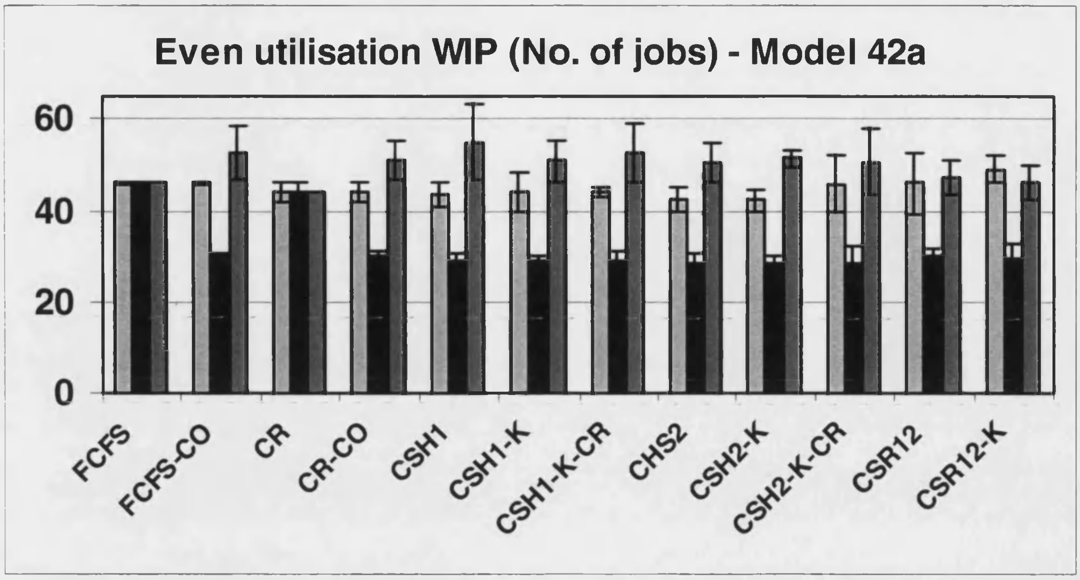


Figure 8.21: Model 42a – Even utilisation plot of WIP (No. of jobs) for *Scenario 1, 2 and 3*, with standard deviations.

Regarding the ATP and WIP measures the Model 42a with even utilisation over all scenarios do not show a large discrepancy between any of the heuristics.

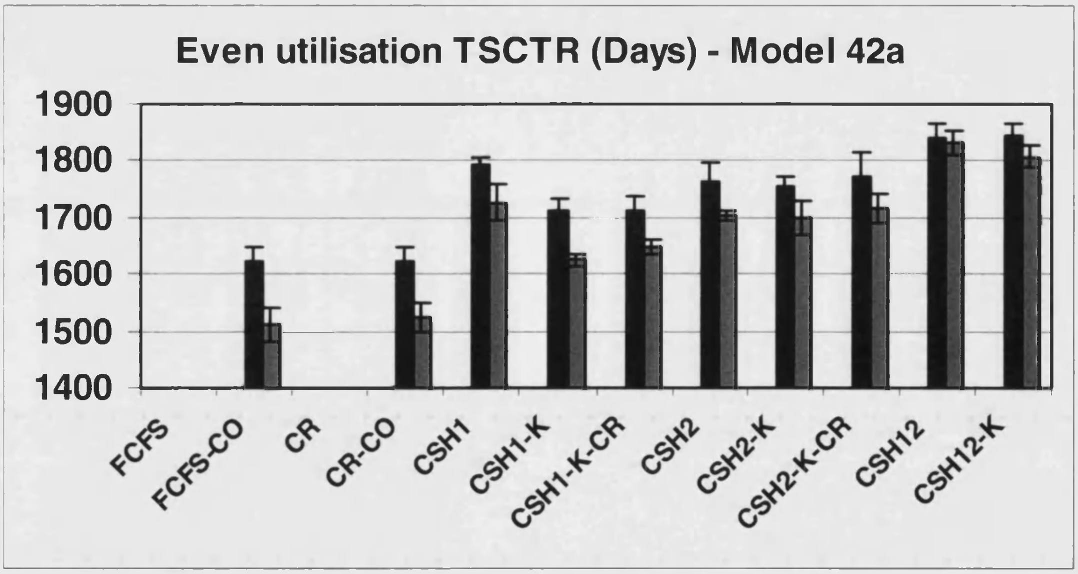


Figure 8.22: Model 42a – Even utilisation plot of TSCT ((Total Sum of Changeover Time Reduction (Days)) for scenario 1, 2 and 3, with standard deviations.

For the TSCTR measure for Model 42a with even utilisation the new heuristics CSH12 and CSH12-K clearly show the largest reduction of changeover time reduction.

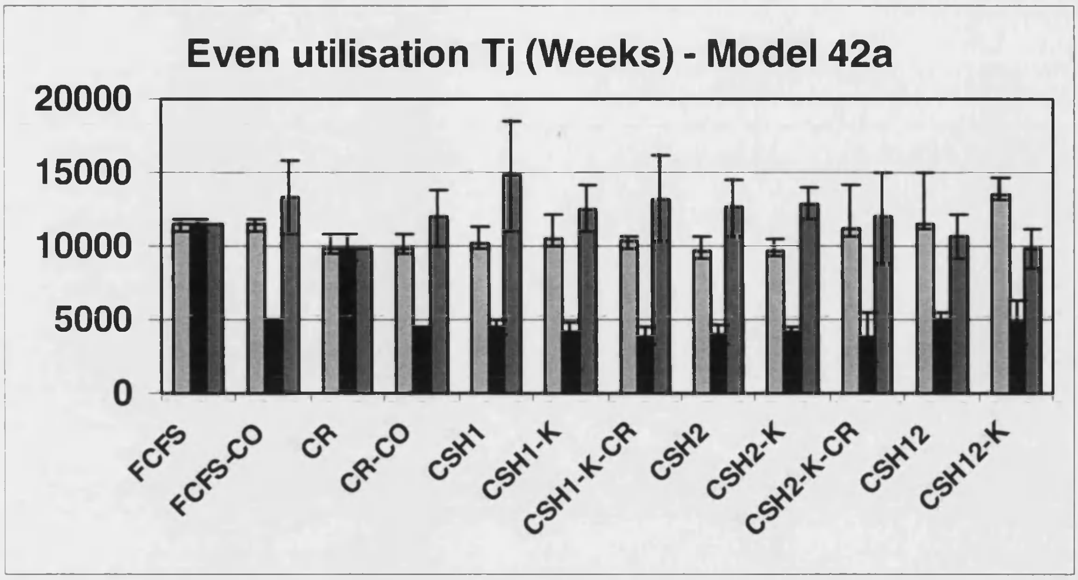


Figure 8.23: Model 42a – Even utilisation plot of Tj **(Tardiness (Weeks))** for *Scenario 1, 2 and 3*, with standard deviations.

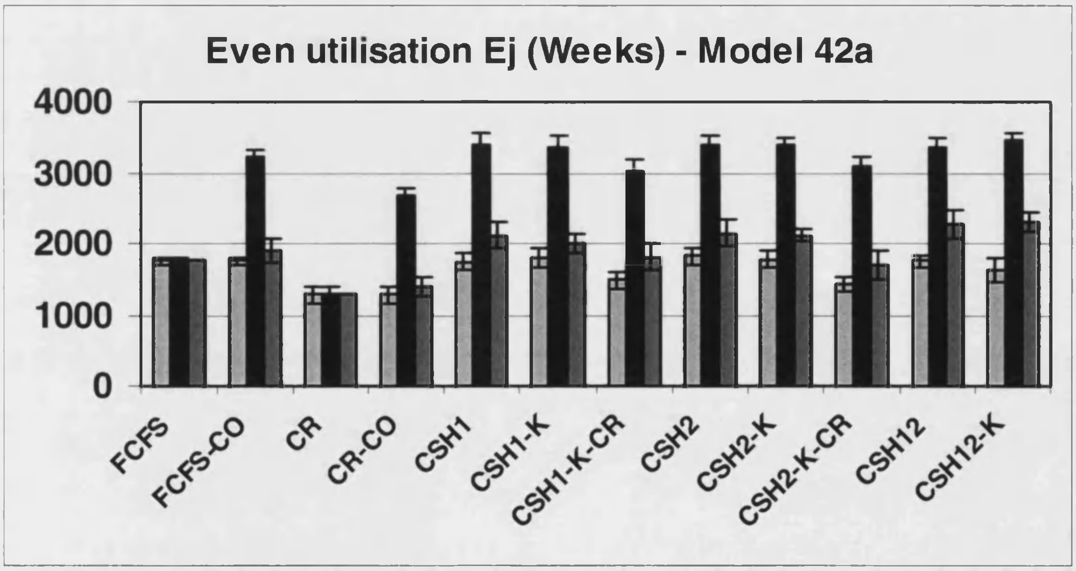
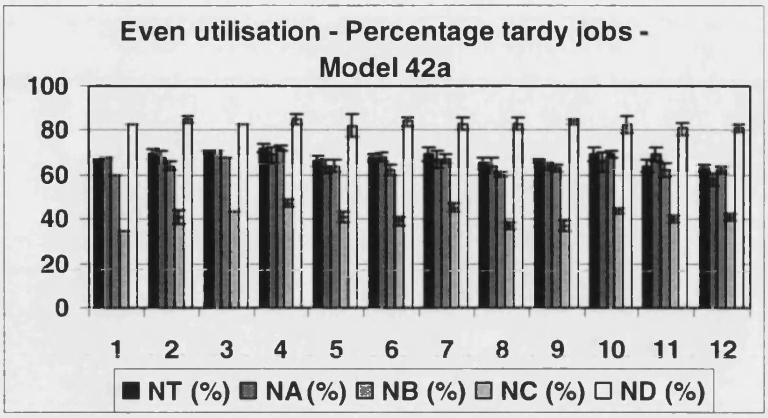


Figure 8.24: Model 42a – Even utilisation plot of Ej **(Earliness (Weeks))** for *Scenario 1, 2 and 3*, with standard deviations.

The earliness and tardiness measures for Model 42a with even utilisation over all scenarios do not show a large discrepancy between the heuristics. However, the new heuristics CSH12 and CSH12-K show some improvement regarding tardiness Scenario 3. The CR heuristics show the lowest earliness of jobs, as explained before this is due to CR attempting to both as few early and as few tardy jobs as possible schedule.

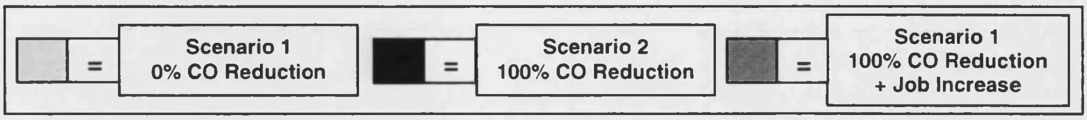
Model 42a

Figure 8.25: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 3*, with standard deviations.



The percentage of tardy jobs for Model 42a with even utilisation over all scenarios, do not show a large discrepancy between the heuristics.

8.7.4 Results from Model 42b with even utilisation (Figure 8.26 to 8.31)



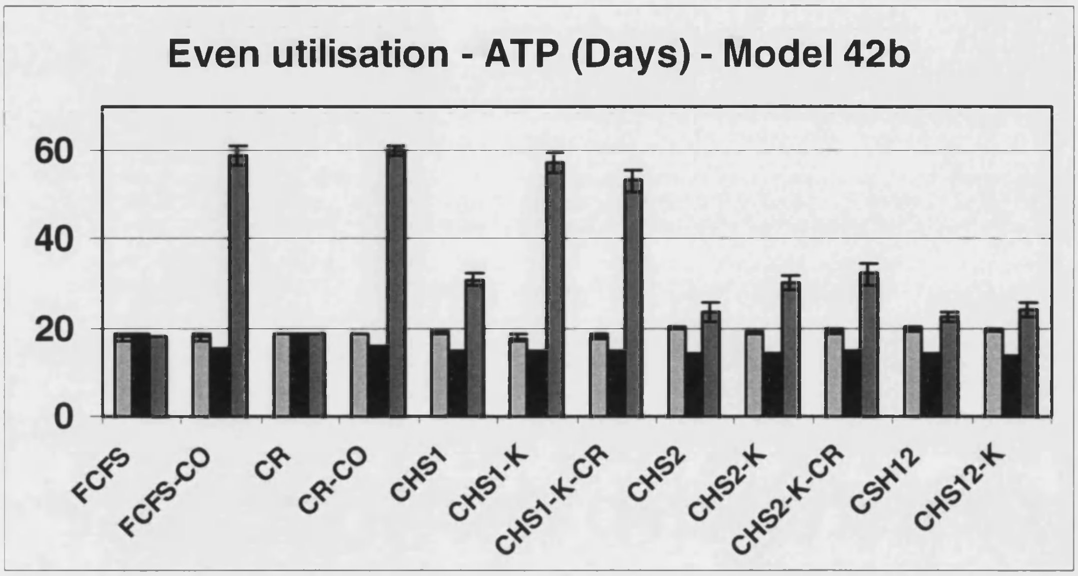


Figure 8.26: <u>Model 42b – Even utilisation</u> plot of ATP (Average Time in Process (Days)) for *Scenario 1, 2 and 3*, with standard deviations.

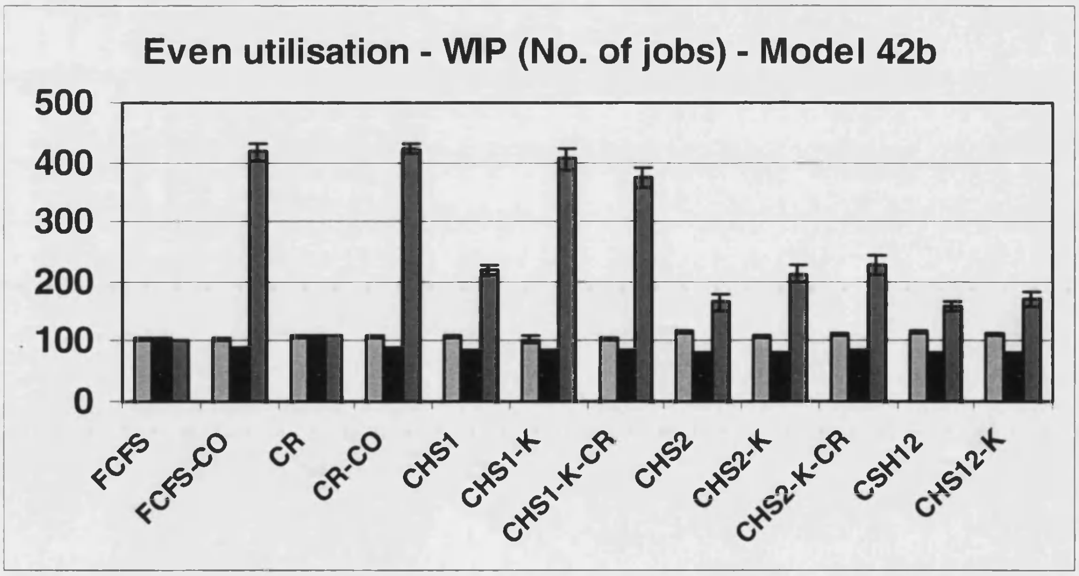


Figure 8.27: <u>Model 42b – Even utilisation</u> plot of WIP (No. of jobs) for *Scenario 1, 2 and 3*, with standard deviations.

Regarding the ATP and WIP measures for Model 42b with even utilisation shows that the best performing heuristics are CSH12 and CSH12-K and the sub-product family heuristic CSH2.

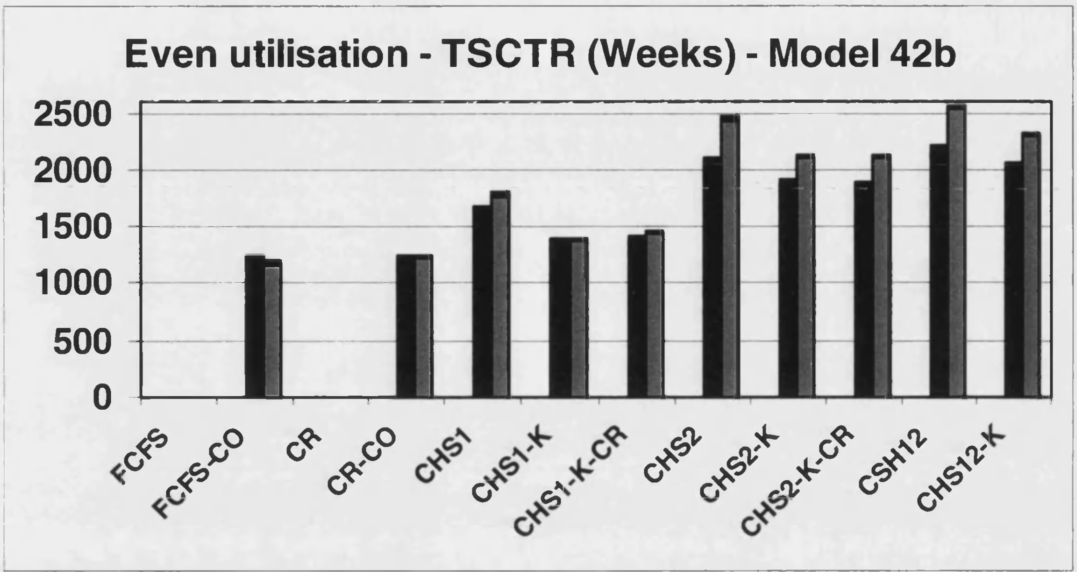


Figure 8.28: Model 42b – Even utilisation plot of TSCTR ((Total Sum of Changeover Time Reduction (Days)) for scenario 1, 2 and 3, with standard deviations.

The TSCTR measure for Model 42b with even utilisation the best performing heuristics are CSH12 and CSH12-K and the sub-product family heuristic CSH2.

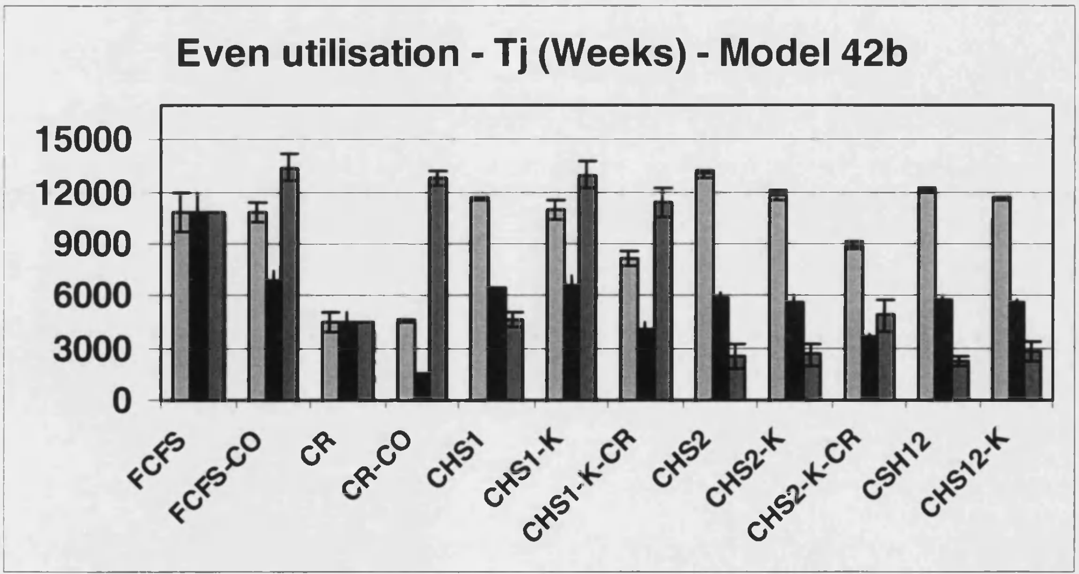


Figure 8.29: Model 42b – Even utilisation plot of Tj (Tardiness (Weeks)) for *Scenario 1, 2 and 3*, with standard deviations.

The tardiness measure for Model 42b with even utilisation, show the very best performance for the new exhaustive heuristic CSH12 over *Scenario 3*. Furthermore, the new heuristic CSH12-K, and the sub-family heuristics CSH2 and CSH2-K perform well.

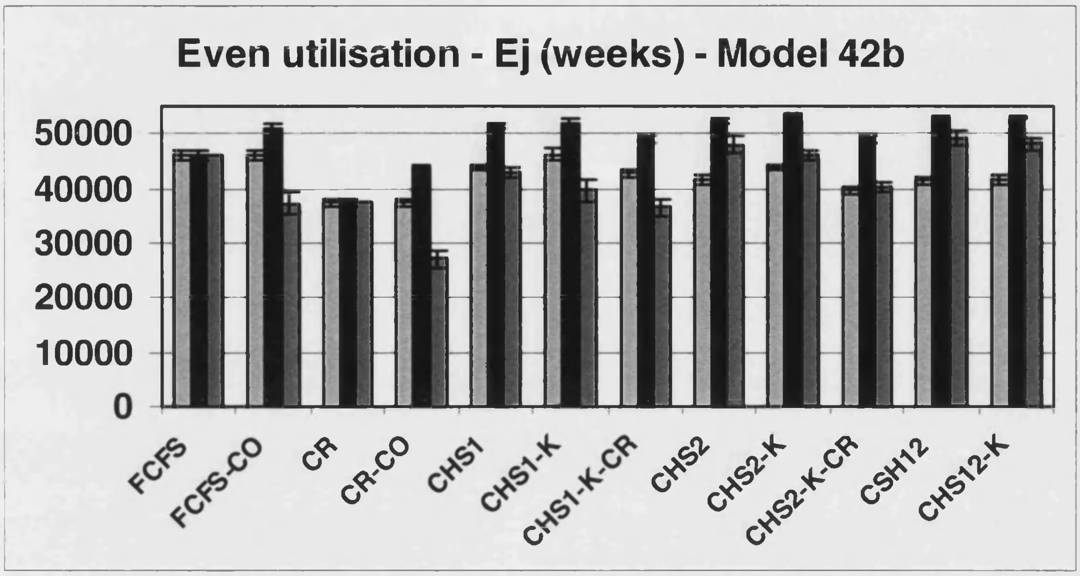
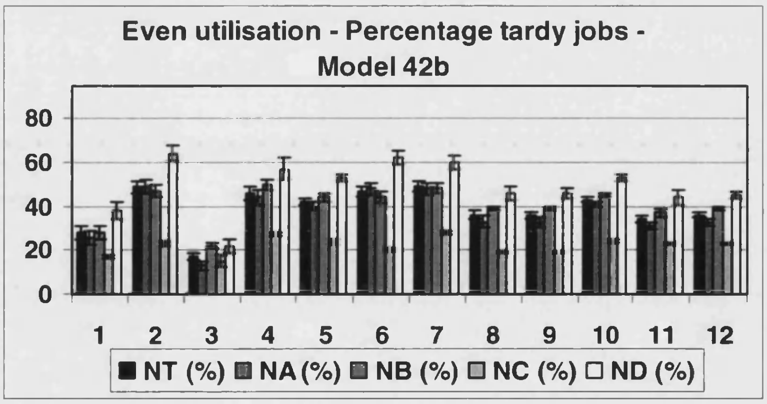


Figure 8.30: Model 42b – Even utilisation plot of Ej (Earliness (Weeks)) for *Scenario 1, 2 and 3*, with standard deviations.

For the earliness measure for Model 42b with even utilisation there is little difference between the heuristics.

Model 42b

Figure 8.31: Plot of N_T, N_A, N_B, N_C and N_D **(% late jobs)** for *Scenario 3*, with standard deviations.



For the percentage of tardy jobs measure for Model 42b with even utilisation, the best performing heuristic is the simple CR heuristic, again this could be because CR considers both earliness and tardiness and tries to balance these.

Model 42b shows more of a difference between the heuristics than Model 42a. It also shows that for measure ATP and WIP, FCFS and CR show a performance similar to or better than most CSHs. However, there are fewer jobs going through FCFS and CR. According to TSCTR the best performing rules includes the two new heuristics CSH12 and CSH12-K. Also CSH2 that schedules according to sub-product family performs well. For tardiness and *Scenario 3* CSH2, CSH2-K, CSH12 and CSH12-K are most competitive over even utilisation. The earliness measure is more even than the tardiness, only CR and CR-CO are lower than the rest, probably the effect of considering due date setting. CR is also the heuristic that showed the lowest number of late jobs.

The difference between the CSHs and the non-CSHs is less obvious when compared over even utilisation. However, the main advantage with CSHs is that with the same utilisation as the FCFS benchmark the CSHs can increase the throughput of Model 42a by 12.5% and Model 42b by 22 %.

8.8 SUMMARY OF RESULTS

This section summarises the main results as discussed and displayed throughout section 8.7.1 to 8.7.4. Ten heuristics and two semi-heuristics for scheduling in a job shop environment were evaluated over a range of performance measures and different experimental factors. The performance of the heuristics can be concluded as:

- The new heuristics that combine product family and sub-product family sequencing, CSH12 and CSH12-K, competed well for both Model 42a and 42b, also when even utilisation is considered. CSH12 and CSH12-K perform especially strong over the Total Sum of Changeover Time Reduction (TCSTR) measure.

- Furthermore, the heuristic that sequenced according to sub-product family (CSH2) showed a worthy performance, whereas the heuristic that sequenced according to product family performed less well (CSH1).

- The Critical Ratio semi-heuristic (CR-CO) could compete with the CSHs for some scenarios, such as tardiness and number of tardy jobs for Scenario 1 and 2. However, when the number of products released into the shop was increased, the performance of CR-CO decreased compared to the CSHs.

- The CR heuristics show the lowest earliness of jobs. This is because CR attempts to schedule both as few early and as few tardy jobs as possible.

- Exhaustive CSHs showed an increased performance compared to non-exhaustive CSHs.

- The difference between the CSHs and the non-CSHs is less obvious when using data sets with even utilisation. However, the main advantage with CSHs is that with the same utilisation as the FCFS benchmark the CSHs can increase the throughput of Model 42a by 12.5% and Model 42b by 22 %.

Experiments (simulation runs) took place that identified in which environments changeover sensitive heuristics are beneficial (e.g. short and long processing times). Furthermore, the performance of the heuristics was evaluated over a range of conditions. In conclusion:

- Long *versus* short and processing times

  The research has shown that CSHs are particularly effective for shorter processing times. This implies that the choice of heuristics is more important for a mix of jobs with shorter processing times. Or the reverse, a mix of jobs with comparatively long processing times is less sensitive to the choice of heuristic.

- Increased batch sizes (increased *utilisation*)

  When the number of jobs released into the shop was increased the CSHs could cope with an increase of 12.5% for Model 42a and 22.0% for Model 42b.

- Processing times for product families

  The product families with overall longer processing times, consistently shown a higher percentage of tardy jobs. This suggests that different due date setting is beneficial for different product families.

CHAPTER 9 CONCLUSION

9.1 CONCLUSION AND DISCUSSION

The motivation of this research was provided by the fact that amongst current scheduling and sequencing approaches there existed few examples based on real world data. Furthermore, the interrelationship between scheduling and sequencing and changeovers had not been previously studied comprehensively. In particular factors such as increased batch sizes and variation in processing time, changeover time and changeover time reduction had not been researched. From the literature review and the industrial surveys undertaken the clear lack of research in this area hinders the development of effective scheduling strategies. It therefore follows that the purpose of the research reported in this thesis was to address these limitations and thereby create more effective sequencing and scheduling policies.

The objectives set out in Chapter 4 have been accomplished:

- Investigation of *existing* scheduling *approaches* and *heuristics* currently applied.
  The literature review focused on scheduling studies with an emphasis on changeover sensitive heuristics. A range of scheduling algorithms and heuristics were studied and compared. The literature review revealed that limitations in current heuristic strategies meant that large sized industrial problems are seldom tackled, especially with complex variables such as changeover issues.

- Analysis of the extent of the use of *scheduling systems* and other approaches in industry.
  A questionnaire survey with 68 responses from a cross section of businesses was carried out in order to investigate industrial approaches to scheduling. A major finding was that only 35% of companies used a scheduling software or package; the majority of companies still preferred a manual scheduling system, such as applying MS Excel.

- Examination of the effectiveness of *existing* scheduling approaches.

  The questionnaire survey and the case study interviews revealed that 33% of respondents were interested in specially developed scheduling software for their needs. This implied that existing software is in many cases inadequate, and was substantiated by the fact that 41% of respondents expressed interest in participating in the present study.

- Ascertain the interdependence between scheduling and sequencing and changeovers.

  An understanding of the relationship between scheduling and sequencing and changeovers, was established through simulation models, literature review and intuition observation.

- Develop *simulation models*, which properly reflect the variables found in real industrial changeover environments.

  Discrete event simulation models of an industrial case study were successfully developed. This was achieved through the use of real data collected from observations of a scheduling process and in-depth interviews with company experts.

- Investigation of a range of heuristics.

  Through extensive experimentation using the simulation models, simple dispatching rules, semi-, and changeover sensitive heuristics, both existing and new, were all tested against each other over ten performance measures. The new heuristics that combines product family and sub-product family sequencing have proved that they are the best performing heuristics for reducing changeover time in a job shop environment with either longer or short processing times.

- Investigate the performance of the heuristics under different experimental factors.

  The testing of the heuristics took place for five major experimental factors, where the level of the factors was varied. The factors were;

  - Different levels of *processing times* (e.g. longer and shorter).
  - Different changeover times, such as *major*, *minor* and *none*.

- Different levels of *changeover time reduction.*
- Increased batch sizes (increased *utilisation*).
- Studying a range of different *performance measures.*

Overall the general aim of the research has been achieved, namely to investigate the relationship between scheduling and changeovers and to develop new scheduling heuristics that are intelligent enough to optimise both due dates and changeover requirements. This has been achieved through a body of case studies, where a range of experimental factors have been tested. The results of the extensive simulations have been concluded into a number of generic conclusions and recommendations.

9.2 GENERIC CONCLUSIONS AND RECOMMENDATIONS

The questionnaire results showed that, although numerous scheduling tools exist, scheduling manually is by far the most common tool applied in industry. This suggests a lack of understanding in the area of production scheduling and that perhaps different aspects of the problems may need consideration and different approaches needed to solve the problem. The reasons companies gave for sticking with the manual scheduling approach emphasised that there is a need for affordable flexible scheduling software with user-friendly interface, user-defined features that can be applied to a company's specific needs and offers re-scheduling abilities that are can be performed within a reasonable time.

Companies that aim to address and improve changeover performance need to consider changeover time reduction through the means of design and organisational changes and improvements. Thereafter, changeover sensitive heuristics should be considered. Depending on product mix and processing characteristics certain principles should be considered. For a product mix that is grouped into product families and sub-product families the proposed heuristics CSH12 and CSH12-K should be considered as they perform well when reducing changeover time. Also CSHs that sequence according to sub-families, CSH2 need be considered, whereas CSH1 that sequence according to product family exhibit lower performance and need not always be considered. The application of CSHs has demonstrated that an increase of jobs into the shop is possible. Hence, applying CSHs will achieve a strong competitive advantage.

The application of exhaustive and non-exhaustive CSHs clearly showed that throughout the experimentation the exhaustive heuristics show a better performance. This means that when jobs continuously are released into the shop, such as daily weekly or monthly (depending on the industrial setting), exhaustive heuristics should be the preferred choice.

The research has demonstrated that depending on the nature of the industrial setting the changeover sensitive heuristics will have different impacts. In particular CSHs are effective for shorter processing times. This suggests that the choice of heuristic is more important for a mix of jobs with shorter processing times. Or the reverse, a mix of jobs with comparatively long processing times is less sensitive to the choice of heuristic. Furthermore, the research has shown that product families with overall longer processing times result in higher percentage of tardy jobs. Thus, suggestion that dissimilar due date setting is beneficial for different product families.

Finally, the research has demonstrated the importance of considering appropriate scheduling and sequencing approaches, when changeovers have been addressed through design and organisational changes.

9.3 SUGGESTIONS FOR FURTHER RESEARCH

It has been outlined that theoretical studies dominate the scheduling literature and industrial case studies incorporating real data sets are rare. The research reported has focused on a flexible job shop environment. Future research for further investigation of interest is in three main areas; namely;

- Using the findings from this research to investigate whether the CSHs would offer the same advantages within the other manufacturing sectors where many changeovers occur, for example food manufacturing.
- Applying the CSHs to account for rescheduling would be interesting.
- Incorporating breakdown, maintenance and the impact of human resources on the CSH would be extremely valuable.

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APPENDIX A

COVERING LETTER AND SURVEY QUESTIONNAIRE

UNIVERSITY OF BATH

15 April 2003

«Company_name»
«Address»
«City_Town»
«Postcode»

Dear «Greetings»,

I am writing to you in the wish that you can help regarding one part of my research. I am currently carrying out a review of scheduling software/packages and I would like to include information about scheduling practises from your company in the review. I hope that you and your company find it interesting to participate in the review. If you decide to do so, please answer the questions on the following pages and return it in the addressed envelope included in this letter by the 2nd of May 2003.

Your answers will be treated with full confidentiality of information and anonymity.

Thank you for your participation and time taken. Please feel free to contact me if you have any questions.

Yours Faithfully,

Ms Kristina Eriksson

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Questionnaire of Scheduling Practice

Please write your answer or tick the box most relevant to your company.

1. **What type of business is your company in?**

___

2. **Is it mainly batch production or continuous production?**

   a) Batch [ ] **b)** Continuous [ ] **c)** Mixed [ ] **d)** Do not know [ ]

3. **What is the weekly output or volume of products?**

   a) Less than 10 [ ] **b)** 10 to 50 [ ] **c)** 50 to 500 [ ] **d)** Greater than 500 [ ]

4. **How many different product variants does your company site manufacture?**

   a) Less than 10 [ ] **b)** 10 to 50 [ ] **c)** More than 50 [ ]

5. **What is the weekly volume of the main variant?**

   a) Less than 10 [ ] **b)** 10 to 50 [ ] **c)** 50 to 500 [ ] **d)** Greater than 500 [ ]

6. **What is your level of changeovers? (How many changeovers per week?)**

   a) Less than 5 [ ] **b)** 5 to 20 [ ] **c)** More than 20 [ ]

7. **What is the scheduling frequency? (How often is scheduling performed?)**

a) Daily	[ ]	*Go to Question 9.*
b) Weekly	[ ]	*Go to Question 9.*
c) Monthly	[ ]	*Go to Question 9.*
d) Other	[ ]	*Go to Question 8.*
e) Do not do scheduling	[ ]	*Go to Question 15.*

8. **If the answer is 'Other', please supply information about how often scheduling is performed at your company site?**

___

9. How does your company perform scheduling? (Please tick several boxes if required.)

a) Manual scheduling [ ] *Go to Question 11.*
b) A scheduling package [ ] *Go to Question 10.*
c) A scheduling module is incorporated in a MRP (Materials Requirement Planning) or an ERP (Enterprise Resource Planning) system Package [ ] *Go to Question 10.*
d) Software developed specifically for your company and production [ ] *Go to Question 11.*
e) Other [ ] *Go to Question 11.*

10. Which scheduling package, MRP or ERP feature does your company use?

____

11. Are you satisfied with the scheduling approach you are using?

a) Very satisfied [ ] **b)** Satisfied [ ] **c)** Unsatisfied [ ]
d) Very unsatisfied [ ] **e)** Do not know [ ]

12. If the answer is 'Other', please supply information about how scheduling is performed at your company site?

____

13. Why has your company decided for the scheduling approach being used?

____

14. Do you use scheduling rules?

a) Yes [ ] **b)** No [ ] **c)** Do not know [ ]

15. Have you looked at scheduling software?

a) Yes [ ] **b)** No [ ] **c)** Do not know about them [ ]

If yes please list packages / types examined

____

____

16. Would scheduling software designed especially for your company's need be helpful?

a) Yes [ ]   **b)** No [ ]   **c)** Do not know [ ]

17. We believe that scheduling is a very important task, however it can be very complicated and is time consuming. If this is something you recognise, can we discuss this with you?

____

18. Would you be willing to participate in our research and would you like us to contact you? If so, please state your details below.

Name ______________________________

Position ______________________________

Company Name ______________________________

Telephone ______________________________

E-mail ______________________________

19. If there are further issues you would like to bring out, please feel free to express yourself below. If more space is needed, please continue on the back of this sheet.

____

____

____

____

____

____

____

____

APPENDIX B

PRE-CASE STUDY INTERVIEW TEMPLATE

Interview Questions

Date Company Name of Interviewee

___________ ________________ ____________________

Category 1 Introductory questions

a) What are your position and your responsibility at the company?

b) What does your company or this company site produce?

c) What is the number of employees at this company or company site?

Category 2 Description of production processes and operational procedures and the complexity of manufacturing processes

a) Can you describe your company's manufacturing processes?

b) What characterise your company's manufacturing processes in relation to production scheduling?

c) Which of the following exist at the company?

- ❑ Changeovers
- ❑ Run-downs
- ❑ Set-ups
- ❑ Run-ups
- ❑ Re-scheduling
- ❑ Contamination issues
- ❑ Differences in the material behaviour, e.g. consistency and contaminations
- ❑ Frequently changing demands from customers
- ❑ Changes in batch size
- ❑ Size of batches frequently differs
- ❑ Demand for smaller and smaller batch sizes
- ❑ High number of ingredients (food)
- ❑ High number of parts to assembly

d) Please give example of occurrences above and when these take place, e.g. contamination issues after changeover?

e) Are any of the occurrences mentioned above taken into consideration when scheduling?

f) Are those occurrences included in the schedule?

Category 3 Manual production scheduling

a) Is manual scheduling the main approach to scheduling?

b) Why is the manual scheduling approach used?

c) Do you feel that your company is content with this approach?

- ❑ Yes
- ❑ No

d) Why do you feel content or discontent?

e) What would you say is the advantages manual scheduling?

f) What would you say is the disadvantages manual scheduling?

g) What software, tools and techniques are used to assist manual scheduling?

h) Would scheduling software be an option for your company?

i) If yes, why?

j) If no, why not?

Category 4 Using scheduling software package or other computerised scheduling tool

a) Is scheduling software the main approach to scheduling?

b) Which software is the company using?

c) Do you feel that your company is content with this approach?

- ❑ Yes
- ❑ No

d) Why do you feel content or discontent?

f) Does the scheduling software fulfil what is required from it?

g) If not, what does it lack?

h) How well does it cope with, for instance, fluctuations in demands and planning of occurrences such as re-scheduling?

i) Is manual scheduling sometimes needed even though scheduling software exist?

j) Please give example when this could be the case.

k) Why is this scheduling approach used?

l) What would they say is the advantages using a scheduling tool?

m) What would they say is the disadvantages using a scheduling tool?

n) Are other tools and techniques used to assist the scheduling software?

o) How was scheduling done before the software was taken into use?

p) What could you say has been improved since the scheduling software was taken into use?

- ❑ Improved product quality
- ❑ Improved machine utilisation
- ❑ Improved use of human resources
- ❑ Improved meeting of deadlines
- ❑ Less work for scheduling people

q) What could you say has become worse since the scheduling software was taken into use?

- ❑ Poorer product quality
- ❑ Poorer machine utilisation
- ❑ Poorer use of human resources
- ❑ Poorer meeting of deadlines
- ❑ More work for scheduling people

Category 5 Identification of scheduling problems and implications

a) What would you say are your company's main problems and implications for more successful scheduling?

Category 6 Successful scheduling solutions and improvements

a) How is your company trying to solve the problems and implications discussed in category 5?

b) What solutions have been applied and to what extent are they working?

c) What is particular difficult to come to terms with?

Category 7 Scheduling Organisation

a) Do you feel scheduling is being given enough attention at the company?

b) Do you feel that management is realising the importance of scheduling?

c) Who and how many are involved in production scheduling?

d) What is their knowledge of the process and is experience necessary?

e) Do you feel that different schedulers deal with scheduling differently?

f) What activities are made to improve production scheduling, for instance regular meetings and training?

g) Are scheduling rules being used?

h) If so what scheduling rules are being used?
(Perhaps more detailed information about this is available)

i) Do you feel that informal scheduling rules exist; for instance, the most important customers order is processed first?

j) Are you meeting delivery dates, e.g. in 90% of all cases?

k) Does your company know how much is lost in time, money, and material for scheduling that did not work?

l) Do you feel that your company has control over WIP at the company?

m) Under what constraints does the scheduling system operates?
(E.g. global management rules like no overtime)

n) Could you describe information and communication between sales, scheduling and manufacturing?

o) Are they using other software without scheduling capabilities, e.g. MRP, ERP?

p) If so which are these software?

q) Are any of the following statements true?

- ☐ Scheduling is a difficult and time-consuming task
- ☐ There are not enough resources for scheduling
- ☐ There is no software sufficient for your needs
- ☐ There is a feeling of acceptance that scheduling is complex and not much can be done to improve this

r) Are there any other issues they would like to raise in relation to discussed topics?